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THERMAL CONDUCTIVITY OF METALS AND ALLOYS AT LOW TEMPERATURES. PART I. A SURVEY OF EXISTING DATA. PART II. THE THERMAL CONDUCTIVITY OF A YELLOW BRASS AND OF CADMIUM

A THESIS

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OF A YELLOW BRASS AND OF CADMIUM

Approved:

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SYMBOLS AND ABBREVIATIONS

Symbols and abbreviations used in Tables I, II, III, and IV are summarized on page 35-36. Certain symbols are gathered for ready reference on page 196 and in various tables. A general summary of symbols and abbreviations follows:

A	area
a	drift rate, °C per minute
a, b	constants
C	centigrade temperature scale
Cp	heat capacity at constant pressure
C_H, C_S	specific heat of head and specimen, respectively
cal	calorie
cm	centimeter
d	differential operator
E, EMF	voltage, electromotive force
e	base of natural logarithms
F	correction defined by equation (29)
Fig.	Figure
ft	foot
hr	hour
I	electric current
K	Kelvin (centigrade absolute) temperature scale
k	thermal conductivity
k'	corrected k, or k per mole
k_e	electronic component of thermal conductivity
k_g	lattice component of thermal conductivity
k_o	residual thermal conductivity
L	length, Lorenz constant
L_e	Lorenz constant based on k_e
L_o	ordinary Lorenz constant
M	mass, molecular weight
min	minute
mm	millimeter
Q	heat
Q_I	heat supplied by specimen heater
Q_o	Q_I corrected for heat flow in leads
q	heat energy as defined in text
R	electrical resistance
R'	ratio of resistance at any temperature to the resistance at 0°C

T	temperature
T_c	$T_m - T_g - 0.02\,°C$
T_B	temperature of copper block
T_g	temperature drop across Vaseline film
T_H	temperature of specimen head
T_m	$(T_H - T_B)/2$
t	time
TCD	difference thermocouple
Th-2	designation for standard platinum resistance thermometer
w	thermal resistance, $1/k$
w_b	due to boundary scattering of lattice waves
w_d	due to scattering of lattice waves by lattice defects
w_e	electronic thermal resistance
w_g	lattice thermal resistance
w_i	due to scattering of electrons by lattice vibrations
w_n	due to scattering of lattice waves by electrons
w_o	due to impurity scattering of electrons
w_u	due to interaction of lattice waves among themselves
x, y, z	directions of the principal axes
α	a constant, thermal diffusivity
Δ	difference of two quantities
θ	Debye characteristic temperature
ν	frequency of lattice vibrations
π	3.1416
ρ	electrical resistivity, density
∂	partial differential operator

ABSTRACT

This thesis was undertaken to compile from the technical literature the values of the thermal conductivity of metals and alloys below room temperature, to measure with an existing apparatus the thermal conductivity of cadmium and of a free-cutting yellow brass between 78 °K and 273 °K and to present a brief review of the theory of heat conduction in metals and alloys. The literature survey included a search of the more common English language abstract journals, particularly Chemical Abstracts. The Landolt-Bornstein Tabellen were relied on for most of the work published prior to 1925. The results of the survey are presented in four tables. Table I contains data for pure metals; Table II, nonferrous alloys; Table III, ferrous alloys; and Table IV, miscellaneous data for various alloy systems at about room temperature. Special mention is made of several reports of extensive experimentation and large compilations of data.

The experimental work was performed in a cryostat built for another purpose which consisted of a large copper block with supporting rods enclosed in a vacuum tight vessel surrounded by a large Dewar flask. The copper block served the dual purpose of supporting the specimen and receiving the heat supplied to the specimen at a substantially constant temperature. The thermal conductivity of the specimen was calculated from its known physical dimensions, measured electrical heat input and temperature gradient under steady state conditions. The electrical heat input was computed from the voltage drop across the constantan heater and a standard resistance in series with it. The temperature gradient was measured with three junction copper-constantan thermocouples which had been previously calibrated. The calibration of the thermocouples involved the calibration of a copper resistance thermometer; the calibration experiment was planned so that the thermometer and the two thermocouples could be calibrated simultaneously using a small copper rod as a heat conductor. This was accomplished by taking a series of measurements at any desired temperature, then heating the head on the specimen to maintain a 2°K to 3°K temperature gradient along the copper rod, measuring the copper thermometer resistance and thermocouple potentials, and finally heating the entire apparatus about 3°K and repeating the first measurements.

The conductivity of the brass was found to vary almost linearly from 0.434 watts/cm-°C at 79.88°K to 1.18 watts/cm-°C at 275.36°K. This is in good agreement with theory and with published values for brasses of similar composition but without the lead. The conductivity of cadmium was found to be 0.940 watts/cm-°C at 81.51°K, 0.914 at 113.92°K (a minimum) and 1.05 at 275.62°K. The presence of a minimum was somewhat unexpected as it was not reported by Lees (Philosophical Transactions of the Royal Society of London, 208A, 381 (1908)), who performed the early experimental work over the temperature range from 100°K to 273°K, and as the conductivity of most metals decreases as the temperature rises. However, a similar minimum has been reported in a few other cases and may be encountered in slightly strained, slightly impure metals. The maximum error in these measurements is estimated to be about 10 per cent. The accuracy is largely dependent on the calibration experiment, which may be responsible for more than half the error.

The arrangement of the calibration experiment suggests that the thermal conductivity of copper could be deduced from the results of the experiment; however, thermal equilibrium was not attained and this could not be done. Failure to attain thermal equilibrium does not invalidate the calibration of the thermocouples. The thermal conductivity of Vaseline (white petroleum jelly) was determined in the experiments with cadmium and brass, and is reported.

A brief discussion of the theory of heat conduction in metals and alloys is presented. Topics discussed include the nature of heat conduction, the electronic and lattice components of thermal conductivity, the thermal conductivity of alloys, the periodic relation and thermal conductivity, other factors affecting thermal conductivity and a section on the prediction and estimation of the thermal conductivity of metals and alloys.

CHAPTER I

INTRODUCTION

Introduction.--The thesis has two distinct and separate parts. Part I consists of a literature survey and a brief theoretical discussion. The purpose of the literature survey was to locate and gather in one place the values of thermal conductivity which have been reported in the temperature range from about 20°K to room temperature. The theoretical discussion includes the nature of heat conduction in metals and alloys and mentions some of the factors which affect thermal conductivity. A discussion of the relation between thermal conductivity and the periodic relation is also included. Part II is a report of experimental work in which the thermal conductivity of brass and cadmium was measured between 80°K and 275°K. The thermal conductivity of vaseline (white petroleum jelly) over this temperature range is also reported.

Literature survey.--A knowledge of the thermal conductivity of metals and alloys is necessary for the design of equipment for use in processes carried out at sub-atmospheric temperatures; it is also a quantity of increasing scientific interest as advances continue to be made in the field of solid state physics. It was therefore considered worthwhile to survey the literature and gather in one place all the published data on the thermal conductivity of metals and alloys, particularly those of engineering importance, between 20°K and room temperature (with some data for temperatures below 20°K included) as no such compilation had been made since the third supplement of the Landolt-Bornstein Tabellen was issued in 1935.[1] Since that time, and particularly in recent years, a considerable amount of investigation has been underway and a rather large and increasing number of articles dealing with thermal conductivity at low temperatures has appeared in the scientific literature. Interest in this field has undoubtedly been enhanced by advances in the theory of conduction and by the increasing commercial importance of low temperature processes such as the liquefaction and separation of the so-called permanent gases, the separation of low molecular weight hydrocarbons and hydrogen, etc.

The results of the literature survey are presented in four tables beginning on page 37. Data in the temperature range of

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[1] Shortly after the literature survey reported in this thesis was completed, Powell and Blanpied in NBS Circular No. 556 (1954), Ref. 88, completed a similar comprehensive survey, the results of which they presented in graphical form.

interest are reported for forty pure metals and about one hundred-fifty alloys. Of these, seven metals and about sixty-five alloys have not appeared in any previous compilation of this scope. Also included are new data for practically all of the metals and many of the alloys, which were scattered throughout the literature. In addition, room temperature data for many alloy systems, which have not previously been compiled, are included.

An abbreviated bibliography and an index to the thermal conductivity data collected in the literature search, prepared for the convenience of the reader, will be found on page 144 and following. The numbers of the references in the abbreviated bibliography correspond exactly to those in the general bibliography at the end of the report. The index was prepared to avoid extensive cross referencing in the tables.

Experimental work.--The purpose of the experimental work was to measure the thermal conductivity of a common leaded brass and of 99.95 per cent cadmium over the temperature range 80°K to 273°K in an attempt to corroborate and extend the work of previous investigators. Available for this work was a cryostat designed for another purpose but which could be used with few alterations to determine the thermal conductivity of a small cylindrical rod from its known dimensions, electrical heat input and temperature gradient. The specimens were chosen on the basis of preliminary calculations which indicated that the apparatus was not suitable for use with materials of very high or very low conductivity. The thermal conductivity of cadmium had not been measured in this temperature range since 1908 and no measurements of the thermal conductivity of brass of this composition had been made below room temperature.

The results obtained for brass are quite satisfactory and agree well with theory and with the results of other investigations of brass of similar composition but without the lead. Its conductivity was found to vary from 0.434 watt/cm °C at 79.88°K to 1.18 watt/cm °C at 275.36°K, the variation with temperature being almost linear, as expected for an alloy. The thermal conductivity of cadmium was found to be 0.940 watt/cm °C at 81.51°K, 0.914 at 113.92°K and 1.05 at 275.62°K. The minimum at about 114°K had not been previously reported; however, there is some evidence (Table I, 88) that a slightly impure, slightly strained metal will have such a minimum.[1] Lees (26), in the only previous work which covers this temperature range, reported the following values for a yellow brass (70 Cu, 30 Zn): 0.732 (extrapolated) at 103°K

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[1] Numbers in parenthesis refer to entries in the bibliography unless preceded by the word "equation".

and 1.06 at 273°K, the variation being approximately linear with temperature; and for cadmium: 1.00 at 103°K and 113°K, and 0.916 at 273°K.

The apparatus and method used in these experiments, while simple in principle, cannot be expected to give highly accurate results. The manner of attaching thermocouples is not completely satisfactory and the unknown heat flow pattern and temperature gradient at the head-specimen interface constitutes an error of unknown magnitude. The accuracy of the experiments is estimated to be within 10 per cent.

PART I

A SURVEY OF EXISTING DATA

CHAPTER II

THEORETICAL DISCUSSION

Introduction.--The theory of conduction processes has been rather rapidly advanced in recent years and much experimental work has been carried out to test the various theories. The primary purpose of Part I is to present the results of a literature survey undertaken to gather the thermal conductivities which have been measured and reported, but a brief review of the theory will be presented. The major factors which affect thermal conductivity include temperature, chemical composition, physical constitution, thermal history and the nature of the metal or alloy itself. The presence of a magnetic field is also important at low temperatures for superconductors, but this phenomenon is beyond the scope of this thesis. Thermal conductivity and the periodic relation is also discussed. Other factors which affect thermal conductivity are discussed and an attempt is made to find a basis for estimating or predicting the value of the thermal conductivity at temperatures below room temperature.

The nature of heat conduction in metals.[1]--In a metal there are two mechanisms by which heat is conducted. These are by lattice waves, as in non-metallic conductors, and by electrons. The contribution of these two mechanisms is generally assumed to be additive:

$$k = k_e + k_g \tag{1}$$

in which k is the total thermal conductivity, k_e is the electronic contribution and k_g is the lattice contribution.

It is generally postulated that the electronic thermal conductivity results from a transfer of heat by electrons in the metal lattice. The electrons are scattered and thermal resistance increased by interaction with the lattice waves and by impurity atoms and lattice defects. The first of these mechanisms is temperature dependent, the second temperature independent. The electronic thermal conductivity is closely connected to the electrical conductivity by the well known Wiedemann-Franz law. The lattice thermal conductivity in a metal is affected by all the factors present in a non-metal and in addition by interaction with the electrons. The free electrons in a metal scatter the lattice waves and in the case of a reasonably pure metal reduce the

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[1] The next five sections are based primarily on the review paper of Olson and Rosenberg (80).

lattice contribution to thermal conductivity to a negligible value. A large impurity content causes k_e to become small, perhaps to the same order of magnitude as k_g, especially at low temperatures where the lattice conduction has a maximum, theoretically, and electronic conduction is small compared to a pure metal.

The electronic component of thermal conductivity. --The electronic heat transfer resistance, $w_e (= 1/k_e)$ is usually assumed to be split into two parts (62). According to Matthiessen's rule these resistances are additive:

$$w_e = w_o + w_i \tag{2}$$

in which w_o is the resistance due to impurity scattering and w_i is the resistance due to scattering of electrons by lattice vibrations, or the ideal resistance. The scattering caused by impurity content and lattice defects, giving rise to w_o, is independent of temperature and is responsible for the residual electrical resistivity, ρ_o, and an associated thermal conductivity which obey the Wiedemann-Franz law:

$$k_o \rho_o = L_o T \tag{3}$$

where L_o is the ordinary Lorenz number valid at high temperatures and T is the absolute temperature. It is interesting that the Lorenz number L_e ($= k_e\rho/T$) approaches the value L_o at high and low temperatures, but in the case of a normal metal such as copper there is a decrease at intermediate temperatures, about 0.1 to 0.2 of the Debye characteristic temperature θ, this decrease being greater for purer metals (80). At room temperature, the ratio L_e/L_o is above 0.8 for monovalent metals, and is somewhat higher if some impurity is present. For an ideally pure metal L_e approaches zero as T approaches 0°K. For the more "non-metallic" metals such as bismuth L_e varies differently (see Ref. 80).

The second of the electron scattering mechanisms, interaction with lattice vibrations, is temperature dependent and gives rise to the ideal thermal resistance w_i. The ideal resistance is represented by a complicated expression which below temperatures of approximately 0.1 θ reduces to:

$$w_i = \alpha T^2 \tag{4}$$

where α is a constant characteristic of the metal. At low temperatures then, equation (2) becomes

$$w_e = \frac{\rho_o}{L_o T} + \alpha T^2 \tag{5}$$

In the intermediate temperature range, the solutions are much more difficult and have only recently been effected (80, 87).

There is fair agreement between theory and experiment. The thermal conductivity increases linearly at the lowest temperatures. As the temperature increases a quadratic term appears in the resistance so that k_e rises to a maximum at approximately $0.1\ \theta$ and decreases monotonically thereafter.

The lattice conductivity. --The lattice conductivity in a metal is affected by all the factors which influence it in non-metals, and in addition by interaction with free electrons. It is generally assumed that the thermal resistance due to each of the several factors is additive:

$$\frac{1}{k_g} = w_g = w_b + w_d + w_n + w_u \tag{6}$$

where w_g is the total thermal resistance of the lattice, w_b is the resistance caused by scattering of the lattice waves at the specimen boundary or at internal grain boundaries, w_d is the resistance due to scattering of lattice vibrations by impurity atoms or other lattice defect, w_n is due to scattering by free electrons and w_u is the resistance due to interaction of the lattice waves among themselves. The latter effect is known as the "Umklapp process".

The temperature dependence of these terms is given by (80):

w_b is proportional to T^{-3} (7)

w_d is proportional to T (8)

w_u is proportional to $T^{\nu} e^{-\theta/2T}$ (9)

where ν is the frequency of the lattice vibrations and e is the base of natural logarithms. The temperature dependence of the term w_n is more complicated and depends on the impurity content, as large amounts of impurities modify the interaction between the electrons and the lattice vibrations (62).

In temperature regions where two of the terms in equation (6) are of the same order of magnitude, the total resistance becomes considerably greater than expected. In a pure specimen the total lattice conductivity will have a maximum at about one-twentieth θ, which may be of the order of 20 watts/cm ^{o}C, or more, depending on the metal (80).

At very low temperatures the boundary resistance is important and k_g varies at T^3. This means that the thermal conductivity approaches the line $L_o T/\rho_o$ asymptotically as T approaches 0^{o}K (62). At slightly higher temperatures scattering by electrons becomes important and k_g varies as T^2 (80). At still higher temperatures, impurities and finally Umpklapp processes become important. The lattice conductivity in the region where scattering is mainly due to electrons has been calculated (80). At $10^{o}K$, this is 0.02 watts/cm ^{o}C for lead, 0.004 for tantalum and about 15 for bismuth. It is obvious that the lattice contribution to the thermal conductivity of metals can be measured only if it is possible to reduce the electronic scattering so that k_g is the most important fraction of the total conductivity. This can be done in some cases by addition of impurities or application of a high magnetic field but will not be discussed here.

The thermal conductivity of pure metals.--Experimental data for pure metals at low temperatures, and particularly for temperatures below that of liquid air, have been meager until recently and still do not cover the entire temperature range thoroughly. The data available agree qualitatively with the theory. For a pure metal, the conductivity increases linearly from $0^{o}K$ to a maximum at about $0.1\ \theta$ and then decreases, sharply if θ is low. The decrease is less steep at higher temperatures. The conductivity at the maximum is usually a few watts/cm ^{o}C, but may be 60 or more if the metal is extremely pure (80, Table I). Theory predicts a minimum in the thermal conductivity at about $0.2\ \theta$, but this is not always confirmed by experiment. It has not been found in copper, for instance, but the results reported in Chapter IV for cadmium indicate a minimum at about 114°K. There is some evidence that there may be a minimum if the specimen is slightly impure and slightly strained (88, Table I).

Graphs of wT against T^3 are often plotted to check the agreement of low temperature experimental results with theory. It would be expected from equation (5) that such curves would be linear and this is found to be true for most metals at very low temperatures. Different samples of the same metal give wT vs. T^3 curves which are very nearly parallel, indicating that the lattice scattering term, α, is the same for each, as required by theory (69). The coefficient of T in equation (5) is due to impurity scattering and is approximately equal to ρ_o/L_o, as follows from theory (80). The presence of impurities causes the curve to deviate from linearity at lower temperatures, and if the impurity content is appreciable the curves are not at all consistant with theory. This is generally attributed to an appreciable lattice conductivity, which indicates that in a very pure metal the conductivity is almost all electronic.

The magnitude of the deviation from linearity of wT vs. T^3 curves to be expected from the theory has been calculated by Olsen and Rosenberg (80). These calculations show that the curve will be linear at very low temperatures and will bend toward the T^3 axis as the temperature is increased. For an ideally pure metal the slope of the curve will be changed by 10 per cent at approximately 0.125 θ and by 15 per cent at 0.144 θ. The deviation starts at progressively lower temperatures as the impurity content increases. The fact that impurity content affects the deviation shows that the ideal and impurity resistance cannot be separated and therefore Matthiessen's rule is only a first approximation.

For most metals the wT vs. T^3 curves are linear up to about 0.1 θ and above this temperature the curve bends toward the T^3 axis. The exceptions are for the most part polyvalent, or otherwise exceptional, metals. The theory applies strictly for monovalent metals, but should give a qualitative picture for the polyvalent metals.

The thermal conductivity of alloys.--The electronic component of thermal conductivity is greatly reduced by the presence of a small amount of impurity. The addition of the first few per cent of impurity has a greater effect than does the addition of the same amount to an already impure specimen. This effect is more pronounced at lower temperatures. This is clearly shown by an inspection of Tables I, II, III and IV.

In an alloy, then, impurity scattering becomes the dominant cause of thermal resistance over a wide temperature range. It overshadows the resistance of lattice vibrations and the curve of k_e shows no maximum but is linear up to rather high temperatures (80). The electronic conductivity k_e is frequently reduced to the same order of magnitude as k_g, which is not greatly affected. These factors cause the curve of thermal conductivity versus temperature for an alloy to differ from that of a pure metal in the order of magnitude involved and by the fact that k_g is a substantial fraction of k whereas in a pure metal k_g is negligible.

If the thermal resistance is dictated by impurity scattering the Wiedemann-Franz law holds and the value of k_e can be determined from measurements of ρ_o. Then

$$k_g = k - \frac{L_o}{\rho_o T} \tag{10}$$

This type of calculation has been made by Hulm (14) for a copper-nickel alloy between 2^o and 20^oK and by Berman (72) for German silver, constantan and stainless steel between 2^o and 90^oK. The results of both investigators indicate that k_g and k_e are the same order of magnitude, and that k_g is proportional to T^2, up to 20^oK. This indicates that in this range the lattice waves are scattered by electrons. Above this temperature the change is more gradual and in the case of Berman's results k_g reaches a maximum in the range 50° to 90°K. Berman has further analyzed the lattice conductivity of German silver and suggests that, while low temperature scattering is due to electrons, scattering due to small scale lattice defects and impurities becomes increasingly important at higher temperatures. This resistance, w_d, begins by being proportional to T, but becomes less temperature dependent at higher temperatures. He also shows that resistance due to boundary scattering, w_b, is about 0.5 per cent at 2°K and decreases rapidly at higher temperatures. However, data for constantan and a copper-manganese alloy taken from Table II indicate that the conductivity k can be changed by as much as 40 per cent by a change in grain size. Earlier work by Karweil and Schafer (66) on German silver, contracid, silver bronze and steel also shows an abnormally high Lorenz number and therefore an appreciable lattice conductivity.

Other factors which affect thermal conductivity. --The foregoing discussion covers the major points of theoretical interest from an engineering viewpoint. Other factors, such as pressure or previous physical and thermal history, might be expected to affect the thermal conductivity of engineering materials. It will be of interest to discuss some of these factors and the magnitude of their effect from an experimental point of view. The experimental evidence on some points is meager and on others the effect must be inferred from electrical conductivity measurements and the Wiedemann-Franz law.

The effect of pressure has been studied by Starr (23) and Bridgman (24) at pressures up to about 12,000 atmospheres. Starr presents a critical review of Bridgman's paper and points out some errors made by Bridgman. The results for copper, silver, gold, tin and lead are considered accurate. The thermal conductivity of each of these metals is found to increase slightly with pressure.

Cold working a metal causes a distortion of the lattice which can interfere with the flow of heat through the metal by scattering both the electrons and the lattice waves. If the metal is subsequently heated to its annealing temperature internal stresses and distortions will be relieved to an extent that depends on the time of exposure to the temperature. Annealing may cause the thermal conductivity to be increased by 15 per cent or more at temperatures above 80°K. At liquid hydrogen temperatures (about 12°K) annealing may cause a 15-fold increase in the thermal conductivity (74, Tables I, II, and III).

The thermal conductivity of a metal or alloy will change when phase changes such as melting or solid state transitions occur. The conductivity of the liquid state is only a fraction of that in the solid state, as expected from the different conduction mechanisms. Solid state phase transitions are responsible for many apparent anomalies in the thermal conductivity-composition curve of certain alloys, such as that of the silver-tin system (see Table IV). This is readily apparent if the curve is compared with the phase diagram (see Ref. 84 for phase diagrams).

Still other factors which may affect the thermal conductivity include anisotropy, porosity, energy changes such as the transition from ferromagnetism to paramagnetism at the Curie temperature, the presence of insoluble phases and the temperature gradient itself, but these are of little engineering importance. Austin (81) presents a qualitative discussion of most of these factors.

Thermal conductivity and the periodic relation. --Many of the physical and chemical properties of the elements can be correlated and predicted from a periodic arrangement of the elements according to their atomic numbers. This is the basis for the periodic "law", which is not a rigid mathematical relation, but is a generalization which has considerable value of a suggestive or qualitative nature. There are many exceptions to this law, the specific heat of metals being a notable one. The periodic relation must be used with caution, but it is valuable once its validity has been established.

Since the thermal conductivity of a metal is closely associated with its subatomic structure by the presence of free electrons, it would seem logical to suppose that some relation between the thermal conductivity and the atomic number should exist. The existence of such a relation in the case of electrical conductivity (82) lends strong support to the assumption of a periodicity in the thermal conductivity, because the thermal and electrical conductivities are related by the Wiedemann-Franz law, equation (3). The relation can be tested by plotting the thermal conductivity against atomic number and noting any periodicity that occurs. The conductivity used for this purpose should be the "atomic" conductivity, i.e., the thermal conductivity per atom, or per mole. The thermal conductivity is ordinarily reported on a volume basis, and a unit volume does not contain the same number of atoms for all metals. To convert the conductivity to the desired basis, the conductivity as reported is divided by the density, d, and multiplied by the molecular weight, M, of the metal:

$$\frac{k\,M}{d} = k' \tag{11}$$

Here k' is the thermal conductivity per mole, or per atom since the molecular and atomic weights of metals are the same. Selected values of thermal conductivity at about 273°K and at about 80°K have been taken from Table I, converted to the mole basis by equation (11), plotted in Figs. 1 and 2, and tabulated in Table I according to periodic groups. The densities and atomic weights were taken from Ref. (83). The thermal conductivity of carbon and of silicon were taken from the <u>International Critical Tables</u>.

An inspection of Figs. 1 and 2, and Table 1 will reveal certain trends which can best be discussed by noting the trends within a periodic group and the changes in conductivity from group to group. Of the nine metals in Group VIII, the thermal conductivity of seven are available. The conductivities of all these metals are of approximately the same order of magnitude, but there is some indication that the conductivity first rises with atomic number, reaches a maximum, and then decreases. The fifth metal in the group, rhodium, has the largest conductivity; however, the last element in the group, platinum, has the second highest conductivity. The presence of a maximum is also indicated in Groups Ib, IIb, and IVb. In Group IIb, mercury, at 273°K, is a

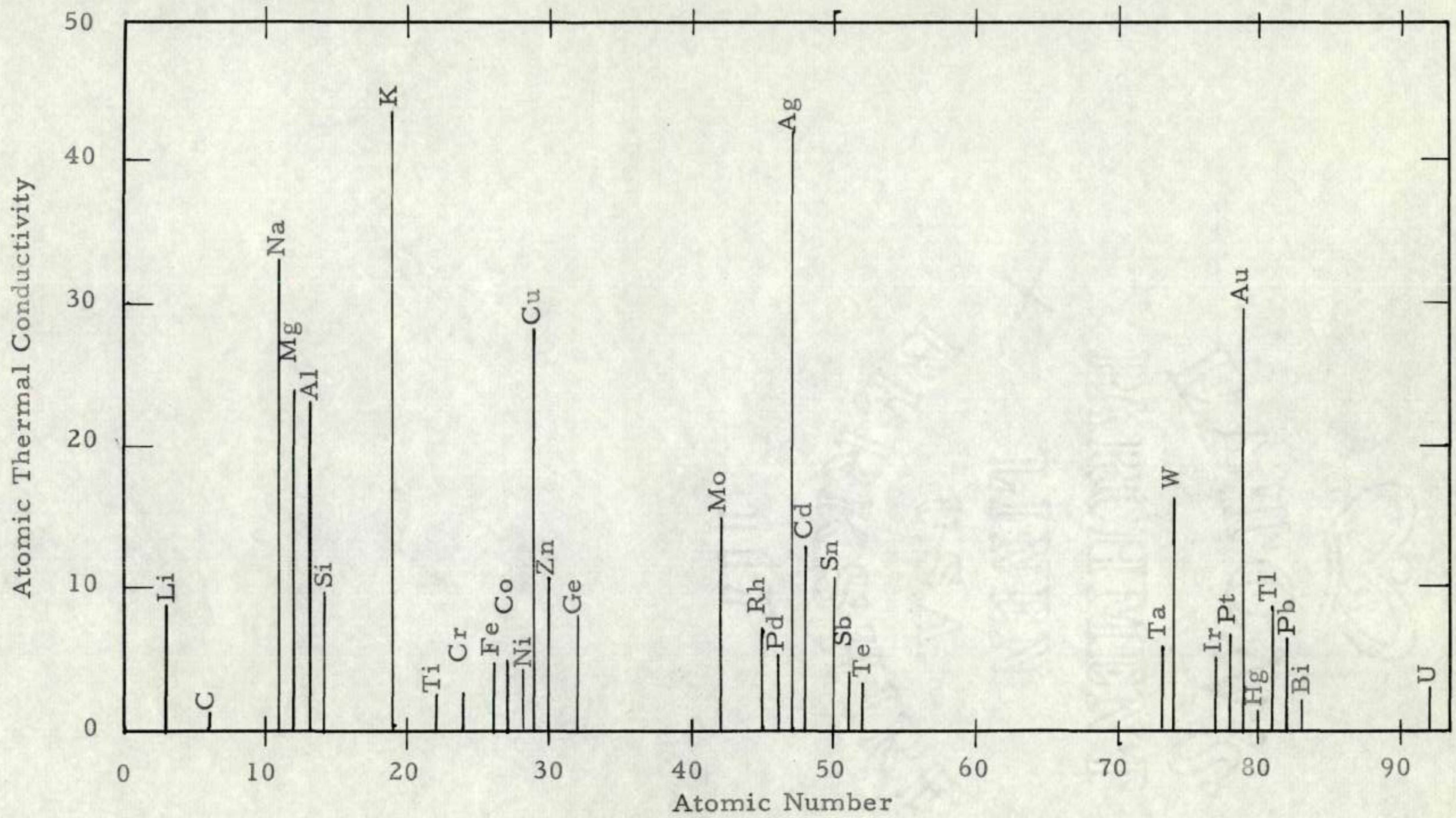

Figure 1

Thermal Conductivity vs Atomic Number Near 273°K

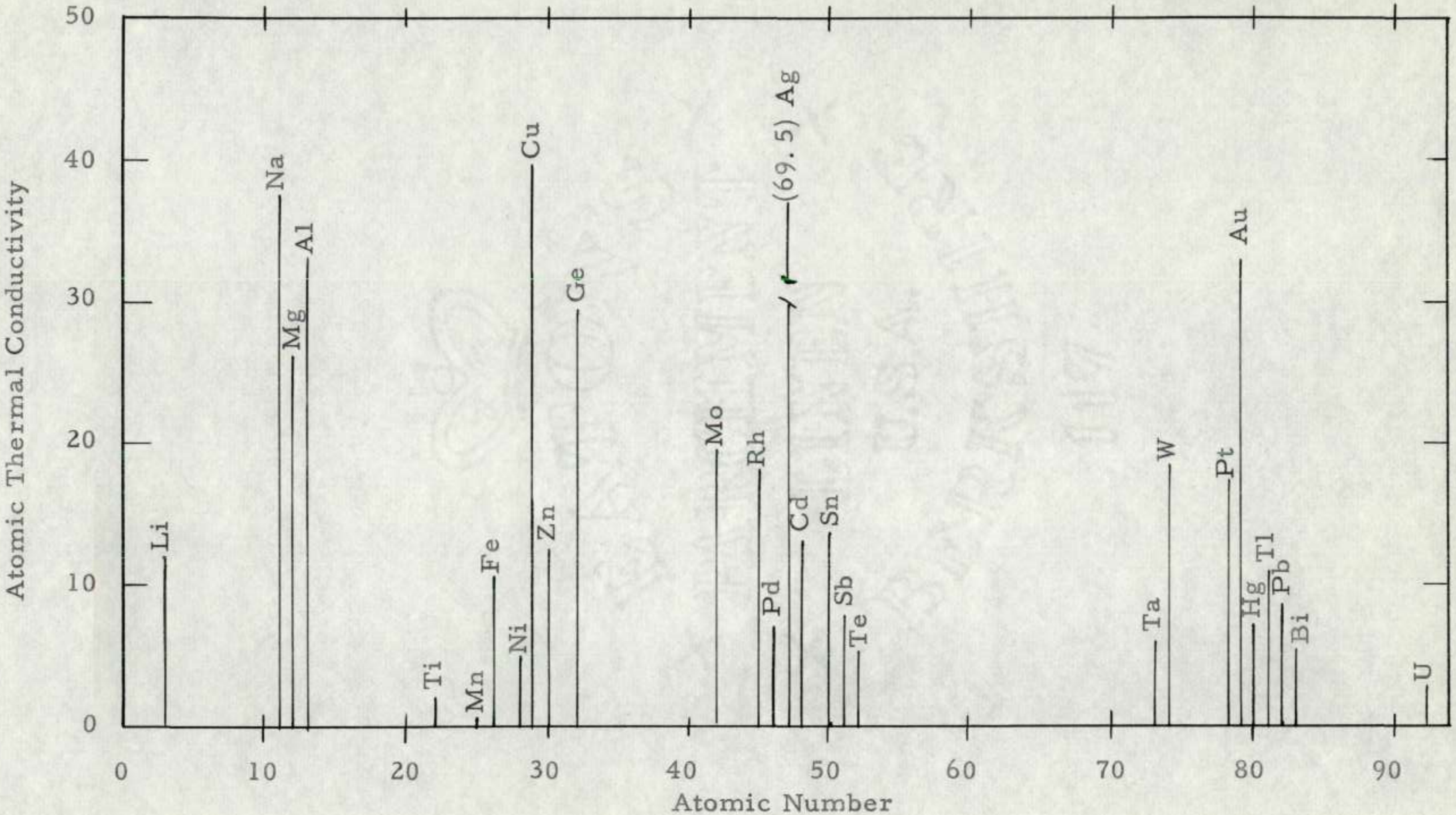

Figure 2

Thermal Conductivity vs Atomic Number Near 80°K

TABLE I

Atomic Thermal Conductivities (1)

Metal	Group	Atomic Number	k_{273}	k_{80}
Lithium	Ia	3	8.42	11.7
Sodium	Ia	11	33.2	36.7
Potassium	Ia	19	44.0	-
Beryllium	IIa	4	7.88	4.16
Magnesium	IIa	12	24.0	26.1
Uranium	IIIa	92	3.31	2.68
Titanium	IVa	22	2.14	1.82
Tantalum	Va	73	5.92	5.92
Chromium	VIa	24	2.20	-
Molybdenum	VIa	42	14.7	19.5
Tungsten	VIa	74	16.3	18.6
Iron	VIII	26	4.26	10.6
Cobalt	VIII	27	4.68	-
Nickel	VIII	28	4.16	4.96
Rhodium	VIII	45	7.26	17.8
Palladium	VIII	46	5.26	6.84
Iridium	VIII	77	5.08	-
Platinum	VIII	78	6.40	7.14
Copper	Ib	29	28.2	39.6
Silver	Ib	47	42.1	69.3
Gold	Ib	79	29.6	33.7
Zinc	IIb	30	10.5	12.5
Cadmium	IIb	48	12.7	13.1
Mercury	IIb	80	1.53	6.84
Aluminum	IIIb	13	22.6	33.0
Thallium	IIIb	81	8.74	11.0

TABLE I (Continued)

Atomic Thermal Conductivities (1)

Metal	Group	Atomic Number	k_{273}	k_{80}
Carbon	IVb	6	0.85	-
Silicon	IVb	14	9.7	-
Germanium	IVb	32	7.80	29.4
Tin	IVb	50	10.9	13.4
Lead	IVb	82	6.40	8.40
Antimony	Vb	51	4.16	8.15
Bismuth	Vb	83	2.18	5.60
Tellurium	VIb	52	3.27	5.51

(1) Expressed in watt cm^{-1} deg. C^{-1} gm $mole^{-1}$

liquid and its conductivity cannot logically be compared with the other metals. Carbon and silicon, though not metals, were included in Group IVb for comparison. The existence of a maximum in this group is open to question as the conductivity of germanium, the third member of the five member group, is apparently less than that of silicon and tin, the second and fourth members, respectively. The conductivity of the three members of Group IVa increases with atomic number but does not pass through a maximum. The data available for the first two members of Group Ia and for the first two members of Group IIa indicate that the thermal conductivity increases with increase in atomic number. The data for the last two metals of Group Vb indicate that the conductivity decreases as the atomic number increases. Data are available for aluminum and thallium, the second and fifth members, respectively, of Group IIIb. In this case the conductivity of aluminum is about 2.6 times that of thallium.

A comparison of the thermal conductivity of the metals in different groups shows that the metals of Group I have by far the highest conductivities. The Group II metals have lower conductivities, about one-third to one-half that of the metals in Group I. Group III contains the rare earth metals and no general statement can be made, although the metals in Group IIIb may have conductivities roughly equal to those in Group II. There is a paucity of data available for Groups IV, V, VI and VII, but such data as there is seems to indicate that the thermal conductivity is at a minimum in these groups, if Groups VIa and IVb are excepted. The conductivity of the metals of Group VIII is somewhat higher, being approximately one-tenth to one-fourth that of the Group I metals.

In only one case has the thermal conductivity of all the metals in a group been reliably established and that is Group Ib, which contains copper, silver and gold. In all other cases either no work has been done or the values that have been found should be verified by further experimentation. Thermal conductivity is a difficult quantity to measure accurately. In addition to the experimental difficulties encountered in its measurement, such things as crystalline structure, grain size, directional effects or anisotropy, and chemical impurities present problems which must be solved before accurate determinations can be made. Much more experimental work must be done before the periodic relation is established beyond doubt.

It is impossible to make a general statement concerning the relation between the thermal conductivity of pure metals and their atomic numbers that is not open to objection. However, it is reasonable to expect that the thermal conductivity of a metal will, in most cases, be the same order of magnitude as the other metals in the same periodic group, and that this relation can be used for predicting the value of thermal conductivity for preliminary or exploratory work.

The thermal conductivity of most metals changes slowly with temperature above about 80°K and the periodic relation discussed above would therefore be expected to hold over a wide range of temperature. That this is indeed the case is shown in Figure 2, which is a plot of the thermal conductivity at about 80°K against atomic number. At lower temperatures than this the periodicity probably holds less well since the conductivity of most metals passes through a maximum in this temperature range. The thermal conductivity of most metals increases as the temperature decreases, but in a few cases such as titanium, uranium and beryllium, for example, the conductivity decreases at lower temperatures. This fact also contributes to reducing any periodicity at low temperatures.

<u>The prediction and estimation of thermal conductivity</u>. --There is no general or completely reliable method for the prediction of the thermal conductivity of metals and alloys. If the thermal conductivity of a reasonably pure metal is desired the periodic relation appears to offer the best method of estimation. The problem is much more involved if the conductivity of an alloy is desired. If the conductivity

of the constituents of the alloy is known, a rough estimate may be made from the fact that the conductivity of an alloy often varies from one-tenth to one-half that of the pure components. The variation may be more if an element such as arsenic, phosphorous or manganese is present. The existence of several solid state solutions in many alloy systems complicates the picture. There is no really satisfactory method for estimating the thermal conductivity of an alloy.

The prediction of the variation of thermal conductivity with temperature is not so difficult. The conductivity of pure metals in general increases with decreasing temperature, the increments being larger at lower temperatures than near room temperature. For example, the conductivity of one specimen of aluminum (5) is 20.0 watts/cm °C at 21°K and only 3.46 watts/cm °C at 80°K. The value at room temperature is about 2.2 watts/cm °C. It should be pointed out that the magnitude of the maximum values, which usually occur at approximately 20°K, is often in doubt because it is greatly affected by small amounts of impurities. In the case of aluminum, for instance, one investigator (69) reports a maximum of 45 watts/cm °C at 16.3°K while another (65) reports a maximum of 9.0 watts/cm °C at 30°K. This is not an unusual case. The agreement at 75°K and above is much better. The increase in conductivity between room temperature and 75°K ranges from ten to twenty-five per cent in most cases.

Alloys in general decrease in thermal conductivity with a decrease in temperature. The conductivity of an alloy at 80° K is generally three-fourths to one-half its value at room temperature. On decreasing the temperature to about 20° K the conductivity is further reduced by a factor of from two to four or five. Below 20° K the conductivity of both alloys and pure metals usually decreases rather rapidly toward zero at the absolute zero of temperature.

CHAPTER III

COMPILATION OF THERMAL CONDUCTIVITIES OF METALS AND ALLOYS

Introduction. --The literature survey was undertaken to compile in one place the available thermal conductivities of metals and alloys, particularly those of engineering importance, in the temperature range 20° to 273° K, with some values above and below this range included. The activity in this field, resulting from theoretical advances explaining conduction processes and the availability of relatively simple cryogenic equipment, has resulted in a rather large amount of information which has been scattered throughout the scientific literature. No attempt had been made to compile this data since the 1923 edition of Landolt-Bornstein Tabellen[1] and its three supplements, the last of which appeared in 1935. Data from the Landolt-Bornstein Tabellen in the indicated temperature range are included in this report. No systematic literature search was made for the period prior to 1925 as it was assumed all available information for this period would be in the Landolt-Bornstein Tabellen.

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[1] See footnote on page 2 and Powell and Blanpied (88). Ref. (88) is a compilation of data for both metals and crystalline solids which was collected from the literature. There is considerable overlap between the present work and that of Powell and Blanpied.

Results of the literature survey are presented in four tables beginning on page 37. Data are reported for forty pure metals and about 150 alloys, much of which has not previously been satisfactorily compiled for ready reference. An index for these tables was prepared to avoid extensive cross referencing. A skeleton outline of references 1 to 78 follows the tables and is given in detail in the general bibliography. The survey was conducted in the library of the Georgia Institute of Technology. The more comprehensive English language abstract and index journals, particularly Chemical Abstracts, the Engineering Index and the Industrial Arts Index, were searched for the period from about 1925 through 1953. The 1952, 1953 and early 1954 numbers of the following journals were also searched in order to bring the survey as nearly up to date as possible.

The Physical Review
The Journal of Applied Physics
The Journal of Scientific Instruments

The following journals were searched for the same period but with one or more numbers missed.

Physica
Proceedings of the Physical Society of London
Proceedings of the Royal Society of London
The Philosophical Magazine

The Landolt-Bornstein Tabellen (1 - 8) were relied on for anything published prior to the period 1925 to 1930.

Several of the references require special comment because they represent rather extensive compilations of data themselves. References (1) through (8) all refer to the Landolt-Bornstein Tabellen, with odd numbers referring to data for pure metals and even numbers to data for alloys. References (1) and (2) refer to the fifth (1923) edition, (3) and (4) to the first supplement, (5) and (6) to the second and (7) and (8) to the third supplement of this edition. These tables were relied on for almost all of the work reported prior to about 1925. An exception to this is the work of Lees (26), who measured the thermal conductivity of nine metals and six alloys between 103°K and room temperature. The work of de Nobel (12) and of Estermann and Zimmerman (11) is extensive and, taken together, they have measured the conductivity of some thirty-two alloys and three metals, all at very low temperatures. Mendelssohn and Rosenberg (65) have measured and reported the thermal conductivity of twenty-three metals at temperatures up to approximately 35°K. The absence of reference to such noted early workers as Gruneisen, Goens, Meissner and others is due to the fact that the results of their work were taken from the Landolt-Bornstein Tabellen.

Mention should also be made of the work of C. S. Smith et al (29, 54), Bungardt and Kallenbach (34) and A. W. Smith (64). These are large compilations of data, most of which are for room temperature or above. C. S. Smith and co-workers report the results of a large program of research on the alloys of aluminum and copper. One report (29) included all the data then available for copper and its alloys. Bungardt and Kallenbach present extensive data for various alloys of aluminum. A. W. Smith investigated the thermal conductivity of twenty-two binary alloys as a function of composition at about 60 °C.

For other sources of information, reference can be made to such work as that of Smithells, Colin J., Metals Reference Book, New York; Interscience Publishers, Incorporated, 1949; to references (30), (83), (84), the International Critical Tables, or many of the engineering and scientific handbooks.

Explanation of the tables.--The four tables, Tables I, II, III and IV, contain the data on the thermal conductivities of metals and alloys which were gathered during the literature survey. In Table I the thermal conductivities of the pure metals are listed in alphabetical order. The non-ferrous alloys, in Table II, and the ferrous alloys, in Table III, are arranged, first, in alphabetical order of the major constituents and, second, in alphabetical order of the remaining constituents. Table IV contains "miscellaneous" data for various alloys, with an arrangement similar to that in Tables II and III. Most of these data are at room temperature or somewhat higher. This table is included for further information only and is not intended to be comprehensive. More data for carbon steels at room temperature are available, but were not included because these alloys become brittle at only slightly below normally encountered atmospheric temperatures and are therefore not used in low temperature equipment.

An index to the tables has been prepared and will be found immediately following the tables on page 144. The purpose of the index is to avoid extensive cross referencing in the tables. Following the index will be found an abbreviated bibliography for the tables. The references also appear, with the same numbers, in the general bibliography. Several of the references are to foreign language publications. In these cases the data were taken from tables or graphs accompanying the article and the text was not read.

The use of abbreviations and symbols in the descriptions accompanying the data was kept to a minimum consistent with good form and easy understanding. The usual symbols were used for the chemical elements. All compositions are in weight per cent unless otherwise indicated. Underlined numbers are uncertain. In some instances the numbers were read from a graph; these cases are indicated by the words "Read from graph" and enough points are recorded to allow reproduction of the curves within reasonable limits. Most metals have a maximum in their thermal conductivity at a very low temperature. In those cases where the data were presented graphically the maximum value has been recorded in the tables.

Numbers in parenthesis were obtained by an extrapolation performed by the original reporters. The method of presentation is as consistent as possible. When the data require a change in the usual presentation, the new method is explained in footnotes if it is not otherwise clear. Most of the original data were reported either in the units watts/cm °C or cal/cm-sec °C. Values reported in the latter unit were multiplied by the factor 4.18633 to convert to watts/cm °C, which is the unit used throughout the tables unless otherwise noted. The complete nomenclature used in the tables and some factors for conversion to other units are given below.

avg	average
bal	balance or remainder
BTU	British thermal unit
ca	approximately
°C	temperature, degrees Centigrade
cm	centimeter
cont'd	continued
C_p	heat capacity at constant pressure
d	density, grams per cubic centimeter
dia	diameter
diff	difference
°F	temperature, degrees Fahrenheit
ft	foot
gm	gram
HP	horsepower
hr	hour
i.d.	inside diameter
in.	inches
°K	temperature, degrees Kelvin
k	thermal conductivity, watts/cm °C unless otherwise noted
max	maximum
millical	millicalorie
min	minute
mm	millimeter

o. d	outside diameter
Ref.	reference
same	used to indicate the same specimen as the one immediately preceeding with exceptions as noted
sec	second
sq	square
SS	stainless steel
T or temp	temperature
Δ T	temperature difference
vol	volume
w	thermal resistance, = 1/k
%	per cent
ρ	electrical resistivity, ohm cm (X 10^6 unless otherwise noted). When ρ is followed by a number in parenthesis, the number is the temperature in °C at which the resistivity was measured

Conversion factors. --To convert watts/cm °C to the units indicated in column A, multiply by the number in column B.

A	B
cal/sec-cm°C	0.2388
cal/min-cm°C	14.33
BTU/(sec-sq ft-°F/in)	0.1926
BTU/(min-sq ft-°F/in)	11.56
BTU/(min-sq ft-°F/ft)	0.9634
BTU/(hr-sq ft-°F/in)	693.6
BTU/(hr-sq ft-°F/ft)	57.80
BTU/(sec-sq ft-°C/in)	0.3467
BTU/(min-sq ft-°C/in)	20.81
BTU/(min-sq ft-°C/ft)	1.734
BTU/(hr-sq ft-°C/in)	1249.0
BTU/(hr-sq ft-°C/ft)	104.0
HP/(sq ft-°F/in)	0.02271
HP/(sq ft-°F/ft)	0.2725
HP/(sq ft-°C/in)	0.04088
HP/(sq ft-°C/ft)	0.4905

TABLE I

Thermal Conductivities of Pure Metals

	T°K	k	Ref.[1]
Aluminum			
Commercial	21.4	1.59	1
	85.0	1.90	
	273	1.93	
0.5 Fe, 0.4 Cu	291	2.01	1
0.75 Fe, 0.38 Si, d = 2.686	301.8	1.94	1
99.98 Al, 0.027 Cu, 0.030 Fe, 0.059 Si	336	2.10	64
Coarse grained casting, tempered 2-1/2 hr at 300°C in vacuum	21	20.0	5
	80	3.46	
Similar crystals, drawn, stretched 2-1/2%, annealed, 5 x 15 mm grains	21	11.9	5
	80	3.45	
Technically pure conducting wire, tempered in vacuum ca 255°C	21	2.93	5
	80	2.67	
Same, stretched 3%, annealed	21	2.13	5
	80	2.45	
Single crystal, fairly pure, recrystallized	21	1.37	5
	80	2.08	
Chill casting, very pure	89	2.54	5
	273	2.25	

[1]References 1-78 are given in skeleton outline on page 139ff and are reported in detail in the complete bibliography.

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Aluminum (Continued)			
99.6 Al, 0.2 Fe, 0.2 Si:			
Single crystal A	288	2.07	5
Single crystal B	288	2.10	
Hardened wire	288	2.07	
Annealed wire	288	2.05	
Single crystal wire	288	2.07	
Utmost purity	80	2.56	7
	273	2.26	
99.7 Al, 0.2 Fe, 0.14 Si	273	2.23	7
	273	2.26	
99 Al, d = 2.70, ρ (21.1) = 2.97	103	(2.19)	26
	113	2.15	
	123	2.13	
	148	2.05	
	173	2.06	
	198	2.06	
	223	2.07	
	248	2.09	
	273	2.10	
	291	2.11	
As rolled, Brinnell hardness = 17	15.73	3.82	12
	17.75	4.17	
	19.32	4.33	
	20.05	4.50	
	24.6	4.83	
	24.8	4.90	
	29.2	5.16	
	29.5	5.21	
	38.0	5.65	
	78.8	3.25	
	86.7	3.00	

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Aluminum (Continued)			
99.995+ Al, 0.002 Mg, less than 0.001 Si, 0.0005 Fe, 0.0005 Cu, faint trace Na, annealed, polycrystal, from Johnson Matthey Read from graph	2.2	10.5	69
	8.2	30	
	16.3	45	
	26.5	36	
99.994 Al, annealed, polycrystal, from Johnson Matthey, read from graph	2.5	0.8	65
	5.0	2.0	
	17.5	6.8	
	30	9.0	
	37.5	8.0	
	46	6.8	
Antimony			
Electric, cast, very pure	83	0.443	1
	196	.263	
	273	.225	
Pressed powder, density ca 1% less than cast Sb	193	0.137	1
	273	.121	
	83	0.248	1
	194	.186	
	273	.159	
Fine crystals, cross sectional area = 0.000141 sq cm	90	0.192	3
	273	.172	
Crystals, cross sectional area = 0.000227 sq cm	90	0.201	3
	273	.172	
Crystals, cross sectional area = 0.000635	90	0.222	3
	273	.180	

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
<u>Antimony (Continued)</u>			
Crystals, cross sectional area = 0.143 sq cm	273	0.247	3
Single crystal, parallel to principal axis	79.5	0.490	50
	91.2	.448	
Single crystal, perpendicular to rod axis	79.2	0.520	50
	91.2	.458	
Single crystal, parallel to rod axis	81.2	0.517	50
	91.2	.462	
<u>Beryllium</u>			
ca 0.5% impurities (Al, Mn, Cr, Fe, Si, Mg)	97.0	0.971	5
	208.2	1.36	
	282.7	1.64	
Perpendicular to hexagonal axis (Specimen 3)	23.2	31.0	48
	80.6	14.93	
Perpendicular to hexagonal axis (Specimen 4)	22.7	25.3	48
	79.0	14.68	
	90.6	11.04	
Perpendicular to hexagonal axis (Specimen 8)	22.6	38.4	48
	79.7	16.42	
	90.9	12.27	
Parallel to hexagonal axis	92.1	14.61	49

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Bismuth			
Electrolytic, cast, very pure	83	0.261	1
	196	.108	
	273	.102	
Pressed powder, very pure, density about 1% less than cast Bi	83	0.208	1
	273	.0812	
Pure	87	0.233	1
	194	.105	
	291	.0803	
	273	0.0740	1
	291	.0812	
Fine crystals, cross sectional area = 0.000167 sq cm	90	0.0962	3
	273	.0669	
Coarse grains, cross sectional area = 0.25 sq cm	90	0.268	3
	273	.113	
Heat flow perpendicular to trigonal axis	300	0.0933	5
Heat flow parallel to trigonal axis	300	0.0581$\underline{7}$	5
99.999 Bi, single crystal, parallel to principle trigonal axis	16.6	0.632	7
	17.7	.627	
	18.4	.577	
	19.6	.573	
	20.1	.506	
	81.5	.167	

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Bismuth (Continued)			
Parallel to secondary axis	16.6	0.770	7
	17.6	0.891	
	18.6	0.920	
	19.6	0.837	
	20.1	0.786	
	81.5	0.259	
Parallel to bisection of two secondary axes	16.6	0.987	7
	17.6	0.987	
	18.6	1.11	
	19.1	1.04	
	20.1	0.996	
	81.5	0.205	
Single crystal, 2 angular axes principal axis = 80°	80	0.187	7
	84.5	0.178	
	89.1	0.176	
	296.5	0.110	
Single crystal, parallel to principal trigonal axis	112.3	0.113	7
	123.6	0.103	
	133.3	0.0933	
	141.0	0.0878	
	142.6	0.0874	
	149.8	0.0828	
	155.9	0.0799	
	160.4	0.0766	
	166.5	0.0749	
	188.0	0.0686	
	195.8	0.0648	
	202.5	0.0619	
	227.5	0.0577	

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Bismuth (Continued)			
Single crystal, perpendicular to principal trigonal axis	104.7	0.196	7
	109.3	0.186	
	117.1	0.171	
	131.8	0.154	
	141.5	0.144	
	152.5	0.132	
	160.0	0.129	
	172.6	0.123	
	188.8	0.116	
	208.4	0.114	
Single crystal, 99.997 Bi (by diff.), 0.002 Ag, 0.001 Pb, minute trace of Cu, trigonal axis parallel to rod axis	19.47	0.719	19
	20.44	0.671	
	21.13	0.613	
	66.71	0.181	
	67.70	0.179	
	67.90	0.178	
	70.63	0.174	
	73.17	0.168	
	75.21	0.164	
	76.87	0.159	
	78.35	0.157	
	79.67	0.156	
	80.44	0.154	
	83.07	0.152	
Single crystal, crystallized 5 times, 99.998 Bi (by diff.), 0.001 Ag, minute trace of Pb, trigonal axis perpendicular to rod axis	19.38	0.769	19
	19.70	0.763	
	19.91	0.757	
	20.22	0.741	
	20.57	0.730	
	21.23	0.675	
	21.93	0.645	
	66.35	0.186	

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Bismuth (Continued)			
Single crystal, crystallized 5 times, 99.998 Bi (by diff.), 0.001 Ag, minute trace of Pb, trigonal axis perpendicular to rod axis (continued)	67.02	0.185	19
	72.83	0.178	
	73.83	0.172	
	75.68	0.167	
	77.08	0.166	
	77.55	0.165	
	78.70	0.163	
	79.54	0.159	
	80.30	0.160	
	81.31	0.160	
Perpendicular to "X" axis	268	0.1943	51
Single crystal, parallel to trigonal axis, $\rho = 0.0144 \times 10^{-6}$ ohm-cm	298	0.0540	52
Single crystal, perpendicular to trigonal axis, $\rho = 0.0114 \times 10^{-6}$ ohm-cm	298	0.0925	52
Cadmium			
Cast, pure, redistilled, d = 8.64, ρ (22.8) = 7.78	103	1.00	26
	113	1.00	
	123	0.996	
	148	0.979	
	173	0.966	
	198	0.950	
	223	0.941	
	248	0.929	
	273	0.916	
	291	0.908	

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T° K	k	Ref.
Cadmium (Continued)			
Purified	20.6	2.34	1
	22.6	1.67	
	87	1.03	
	273	0.937	
Pure "Kahlbaum"	20.6	1.87	1
	22.5	1.83	
	87	1.02	
	273	0.975	
	83	1.23	1
	194	1.02	
	273	1.01	
	273	0.926	1
	273	0.920	
Pure	291	0.927	1
Single crystals, pure, undeformed, parallel to hexagonal axis	21	1.80	7
	83	0.904	
	293	0.832	
Same, perpendicular to hexagonal axis	21	2.00	7
	83	1.13	
	293	1.04	
99.999 Cd, cast in glass, from Hilger, read from graph	2	7	65
	5	12	
	12	4.5	
	21	4	

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Chromium			
	195.8	0.347	27
	195.5	0.341	
	273.5	0.292	
	274.0	0.292	
	299.0	0.267	
	299.4	0.266	
	316.5	0.262	
	316.9	0.262	
	333.9	(0.282)	
	334.4	(0.275)	
Cobalt			
0.24 C, 1.4 Fe, 1.1 Ni, 0.14 Si	303	0.692	1
Columbium			
99.99 Cb, annealed, from Johnson Matthey, read from graph	2	0.01	65
	6	0.06	
	9	0.15	
	22	0.33	
Copper			
Pure, soft drawn, d = 8.84, $\rho(16.9) = 1.750$	103	(4.652)	26
	113	4.514	
	123	4.409	
	148	4.17	
	173	4.07	
	198	4.01	
	223	3.95	
	248	3.90	
	273	3.87	
	291	3.83	

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Copper (Continued)			
Electrolytic, especially pure	20.4	18.82	1
	90	4.98	
	273	3.92	
Electrolytic, very pure	20.4	17.2	1
	90	4.65	
	273	3.85	
Natural crystals	21.0	122	1
	73	8.16	
	83	5.94	
	273	4.10	
Technical	22	13.1	1
	85	4.73	
	196	4.02	
	273	3.93	
Pure	291	3.73	1
	291	3.91	
	293	3.94	
Pure electrolytic	303	3.81	1
With a trace of As,	291	1.42	1
Single crystal, cut from large block, not entirely pure	21	19.0	5
	83	5.15	
Same, tempered 7-1/2 hr at 380°C	21	25.3	5
	83	5.27	

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Copper (Continued)			
Forge hammered from 6 to 2.5 mm dia., tempered 3 hr at 380°C	21 83	25.7 5.36	5
Same, annealed 5 min. in vacuum at 950°C, ca 25 crystals per sq mm	21 83	20.4 5.23	5
Similar, 3 - 4 grains per gauge length, untempered	21 83	19.0 5.15	5
Same, tempered 4 hr at 380°C	21 83	27.4 5.31	5
Single crystals, melted and solidified, undeformed and unworked, not very pure	21 83	11.4 5.02	5
Natural crystals, prepared from a single grain, tempered at 380°C, very pure	21 83	79 to 92 5.56	5
Natural crystals, very pure, tempered at 380°C, porous	21	88.0	5
From a bloom, forge hammered from 3 to 1.3 mm dia.	21 83	24.1 5.23	5
Same, tempered 3 hr at 380°C	21 83	87.8 5.56	5
Purest electrolytic, fine grained	21 83	54.4 5.48	5
Same, unworked	21 83	49.4 5.40	5

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Copper (Continued)			
Purest electrolytic, fine grained, tempered 4.5 hr at 380°C	21 83	56.9 5.40	5
Uniform unworked sample, tempered 4.5 hr at 380°C, then 5 min. at 950°C	21 83	46.4 5.31	5
Single crystal, unworked	98.4 235.5 292.6	4.73 4.41 4.14	5
Natural crystals, hammered 3 to 1.3 mm dia, tempered 3 hr at 380°C, $\rho_o = 1.56 \times 10^{-6}$ ohm-cm	21.4 78.9	82.0 5.77	7
Pure electrolytic	273	3.91	7
Electrolytic	ca 273	3.84	58
99.986 Cu, 0.022 O, 0.0016 Fe, 0.0015 S, annealed 1 hr at 550°C, air cooled, avg grain dia = 0.075 mm	293	3.94	29
Thin wire, 0.2 mm dia, not very pure	15.5 17.1 18.6 21.8	23.8 22.7 20.4 18.2	17

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Copper (Continued)			
Annealed electrical wire, doubtful purity	10	7.95	15
	15	10.0	
	20	12.1	
Also: $k = a + bT$ (ca 5° to 20°K), where a = 900, b = 100, units will be millical/(cm-sec-deg)			
99.999 Cu, annealed, polycrystal, from Johnson Matthey, read from graph	2	5.8	65
	10	28	
	17	33	
	29	27	
	40	16	
Only impurities: ca 0.0005 Ag, less than 0.0003 Ni and 0.004 Pb. Drawn into wires 1.12 and 0.45 mm dia, annealed 6 hr at 450°C in He, read from graph	2.5	11	67
	6.0	15	
	17.0	49	
	28.0	40	
	34.0	26	
	45.0	15	
	65.0	7	
	92.0	5	
Also: $1/k = 0.212/T + 2.55 \times 10^{-5}T^2$ (12° to 30°K) units, watts/(cm °C)			
Gallium			
Preliminary observations on 99.99 Ga:			
Parallel to c axis	Room	0.84	47
Parallel to a axis	Room	1.7	
Parallel to b axis	Room	4.2	
Specimen: orthorhombic crystal, c axis parallel to pyramid axis, b and c axes coincide with diagonal of pyramid base, b axis is the good (best) conducting one			

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Gallium (Continued)			
At 20°K, for the equation $w = 1/k = AT^2 + B/T$, the constants A are in the ratio 1:4:10.5 for the c, a and b axes, respectively. B has a similar anisotropic effect. At 40°K, w is in the ratio 1:2.3:5.2 for the three axes. See Ref. 70.			
Germanium			
Single crystal, n-type, ρ = ca 10 ohm-cm, 5/16 sq in cross section by 3/4 in long. Long dimension oriented along a 100-crystal axis	298	0.586	13
High purity, cast single crystal, 1/4 in dia rod, accuracy ca 20%, room temp ρ = 0.30 ohm-cm	3.7	0.487	62
	10.2	2.76	
	14.0	3.66	
	15.0	3.95	
	15.9	3.85	
	16.0	4.2	
	16.9	4.10	
	17.3	3.95, 4.32	
	19.1	3.98, 4.15	
	20.2	4.45	
	20.5	3.95	
	20.6	3.11	
	63.5	2.97	
	66	2.55	
	70	2.60	
	75	2.27	
	79	2.21	

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Germanium (Continued)			
0.006 atomic % Al, 1/8 in dia rod, room temp ρ = 0.0021 ohm-cm, accuracy "much better" than 20%	2.72	0.0265	62
	3.59	0.0479	
	3.87	0.0581	
	14.5	0.995, 1.00	
	15.8	1.09, 1.19	
	18.1	1.31, 1.28	
	19.7	1.38, 1.51	
	20.4	1.76, 1.53	
	63.6	1.90	
	67.2	1.82	
	68	1.90	
	69	1.87, 1.64	
	70	1.72	
	78	1.62	
	86	1.67, 1.73	
n-type, ρ = 0.005 ohm-cm at room temp	4.2	0.36	71
n-type, ρ = 0.013 ohm-cm at room temp	55	4.0	71
	80	2.5	
p-type, ρ = 0.2 ohm-cm at room temp	55	5.0	71
	80	2.5	
Gold			
0.001% impurities	20.4	15.1	1
	90	3.22	
	273	3.11	
Pure	291	2.93	1

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T° K	k	Ref.
Gold (Continued)			
d = 19.49	290	2.95	3
Forged	297	2.98	5
Annealed	297	2.98	5
Single crystal, very pure, unworked, avg of 2 values	21 83	15.6 3.34	5
Original single crystal, forged, tempered 5.5 hr at 380°C	21 83	15.5 3.32	5
Rod from Jaeger and Diesselhorst forged twice at glowing heat, untempered, technically pure	21 83	3.53 2.90	5
Same, tempered ca 3 hr at 390°C	21 83	4.16 2.96	5
Forged, untempered, very impure	21 83	3.39 0.866	5
99.99 Au	273	3.06	10A
99.999 Au, polycrystalline wire, from Johnson Matthey, read from graph	3 13 21	3 9 7	65

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Gold (Continued)			
99.9 Au, Impurities: Ag, traces of Pt, faint traces of Cu, Fe, Pb and Sn. Read from graph	3	1.8	75
	22	4.3	
	66	3.1	
	142	3.3	
Same, annealed, read from graph	2	1.3	75
	18	6.2	
	20	5.0	
	75	3.3	
	150	3.5	
99.999 Au with spectral lines of Ag and Cu, faintly visible lines of Cd, Fe, Mg and Na, very faintly visible lines of Ca and Zn, read from graph	2	1.2	75
	14	7.9	
	38	4.5	
	70	3.2	
	150	3.5	
Same, annealed, read from graph	2	10.3	75
	ca 12	ca 28	
	38	6.0	
	70	3.5	
	150	3.6	
Indium			
99.993 In, polycrystalline wire, from Johnson Matthey, read graph	2.0	5.7	65
	3.5	7.8	
	4.5	8.4	
	7.5	7.1	
	16	2.4	
	33	1.2	

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T° K	k	Ref.
Iridium			
d = 22.33	290	0.590	3
99.995 Ir, annealed wire, from Johnson Matthey, read from graph	2 21 34	3 16 10	65
Iron			
99.42 Fe, 0.001 C, 0.0015 Mn, 0.0013 Si, wrought, d = 7.74, ρ (19.9 = 14.33	103 113 123 148 173 198 223 248 273 291	(0.632) 0.636 0.640 0.644 0.636 0.627 0.619 0.615 0.615 0.615	26
Cast, 31 kinds (d = 6.85 - 7.22) averages; d = 7.28	281	0.389-0.640 0.489	1
Cast, 3.5 C, 0.5 Mn, 1.4 Si	303	0.623	1
Malleable, 0.09 C, 0.31 Mn, 0.11 Si, 0.29 Cu, 0.03 P, 0.03 S, annealed at 900° C	303	0.410	1
Malleable, 0.1 C, 0.1 Mn, 0.2 Si	291	0.601	1
Malleable, 0.105 C, 0.06 Mn, 0.015 Si, 0.05 Cu, 0.03 P, 0.015 S, d = 7.87	291	0.715	1

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Iron (Continued)			
Double electric refined, forged and tempered	21 83	5.61 1.51	5
Electrolytic, polycrystalline, technical, untempered	21 83	3.01 1.36	5
Electrolytic, repeatedly forged, tempered 1 hr at 500°C	21 83	0.494 0.908	5
Technically pure	273	0.774	7
Electrolytic, 10 crystal boundaries per cm	80 273	1.84 0.941	7
Electrolytic, 170 grain boundaries per cm	80 273	1.83 0.899	7
Electrolytic, 634 grain boundaries per cm	80 273	1.18 0.824	7
99.2 Fe, 0.02 C, 0.02 Mn, 0.02 S, 0.01 P, 0.01 Si	273	0.740	7
Pure, annealed in vacuum	289.6	0.661	7
Wire, 99.88 Fe, 0.011 C, 0.017 Mn, 0.006 P, 0.026 S, 0.056 Cu, 0.002 Si	80.16 194.66 273.16	0.937 0.715 0.706	10
0.0045 C, 0.0002 Si, 0.001 P, 0.0006 Ni, 0.002 Mn, trace of Mg, Al	273 298	(0.812) 0.791	37

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Iron (Continued)			
Purest electrolytic	5.0	0.431	66
	10.0	0.760	
	15.0	1.110	
	20.0	1.470	
99.93 Fe, as forged, Brinell hardness = 103	15.77	0.518	12
	16.79	0.586	
	19.35	0.634	
	21.37	0.738	
	23.85	0.838	
	26.4	0.945	
	38.4	1.224	
	52.0	1.305	
	67.1	1.099	
	76.8	0.931	
	93.0	0.935	
99.99 Fe, annealed, from Johnson Matthey, read from graph	2	0.30	65
	27	2.40	
	33	2.55	
Lead			
Pure, d = 11.29, ρ (17.4) = 20.9	103	(0.389)	26
	113	0.385	
	123	0.381	
	148	0.372	
	173	0.364	
	198	0.356	
	223	0.356	
	248	0.351	
	273	0.351	
	291	0.347	

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Lead (Continued)			
0.0002 impurities	20.4	0.485	1
	90	0.376	
	273	0.350	
Technical	20.6	0.477	1
	26.4	0.452	
	85.9	0.397	
	273	0.330	
Pure "Kahlbaum"	20.8	0.544	1
	26.1	0.489	
	86.2	0.385	
	273	0.372	
	90	0.452	1
	261	0.385	
	298	0.345	
Very pure	23	0.525	5
	73	0.471	
	123	0.432	
	173	0.402	
	223	0.376	
	273	0.353	
	323	0.332	
	23	0.535	5
	73	0.473	
	173	0.406	
	273	0.351	

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Lead (Continued)			
Avg value from 2 rods	11.1	1.05	17
	13.0	0.571	
	14.6	0.735	
	17.3	0.621	
	19.1	0.565	
	21.0	0.524	
	25	0.500	
	34	0.442	
	43	0.426	
	77	0.397	
Pure, melted in vacuum and frozen into a single crystal	14.38	0.913	16
	15.47	0.730	
	15.57	0.746	
	15.85	0.714	
	17.63	0.658	
	17.92	0.633	
	20.19	0.575	
	21.31	0.552	
	22.70	0.526	
99.998 Pb, single crystal in normal state, read from graph, high sharp maximum ca 2.5°K	2	11.0	65
	5	16.5	
	10	1.5	
	40	0.5	
Lithium			
	20.5	2.050	3
	91.0	0.837	
	273	0.711	

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Lithium (Continued)			
	23	4.18	5
	73	0.912	
	98	0.866	
	123	0.837	
	148	0.803	
	173	0.774	
	198	0.740	
	223	0.711	
	248	0.682	
	273	0.648	
	293	0.623	
Chill casting, very pure	80	1.87	5
	273	1.72	
Magnesium			
	273	1.57	1
99.95 Mg, 0.028 Fe, 0.014 Si	336	1.50	64
0.18 Si, 0.005 Al, 0.01 Fe, cast, untempered	303	1.48	3
Same, annealed at 450°C	303	1.53	3
Utmost purity	80	1.87	7
	273	1.72	
99.95 Mg, polycrystal, from Johnson Matthey, read from graph	2	3.2	65
	14	9.1	
	17	9.7	
	36	6.2	
	48	4.5	

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Magnesium (Continued)			
99.98+ Mg, 0.013 Fe, 0.0023 Mn, 0.0013 Pb, faintly visible spectral lines of Si, Cu, Ag, Ca, and Na, as drawn, from Johnson Matthey, read from graph	3	2.0	73
	12	9.0	
	20	10.0	
	33	7.0	
	58	3.0	
	70	2.0	
	150	1.6	
Same, annealed, read from graph	2	2.6	73
	7	9.0	
	17	14.2	
	37	7.0	
	55	3.0	
	70	2.0	
	150	1.6	
99.95+ Mg, main impurities: 0.03 Mn, 0.0075 Fe, 0.004 Al, annealed in vacuum 6 hr at 500°C	3.0	2.1	78
	4.5	4.0	
	8	7.1	
	18	9.8	
	27	9.2	
	34	7.8	
Manganese			
beta-Mn	83	0.050	7
99.99 Mn, annealed, from Johnson Matthey, read from graph, ca linear in range shown	2	0.002	65
	32	0.03	

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Mercury			
Solid	3.9	1.67	1
	4.9	1.13	
Solid	83	0.485	1
	157.7	0.389	
	194.8	0.325	
	229.0	0.278	
(liquid)	236.0	0.0912	
	252.5	0.0975	
	273	0.104	
	323.6	0.125	
Single crystal, parallel to principal axis	86	0.397	7
	196	0.341	
Single crystal, perpendicular to principal axis	86	0.289	7
	196	0.264	
Molybdenum			
d = 9.933	290	1.45	3
Very pure, annealed at 220°C	273	1.40	10A
Same, annealed at 900°C	273	1.43	10A
Somewhat less pure, annealed at 220°C	273	1.32	10A
0.01 Al, 0.05 Bi, 0.05 Cd, 0.001 Co, 0.001 Cu, 0.01 Ge, 0.001 Pt, 0.001 Rh, 0.01 Sn, 0.01 Ti, trace of C, V, W	90.20	1.83	10
	194.70	1.36	
	273	1.37	

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Molybdenum (Continued)			
Same, different specimen	90.20	1.80	10
	194.70	1.38	
	273	1.38	
99.95 Mo, from Johnson Matthey, read from graph	2	0.30	65
	22	2.95	
Nickel			
99 Ni, d = 8.80, ρ (22.1) = 13.07, less than 1% impurity	103	(0.535)	26
	113	0.540	
	123	0.544	
	148	0.552	
	173	0.561	
	198	0.569	
	223	0.573	
	248	0.581	
	273	0.586	
	291	0.586	
97.0 Ni, 1.4 Co, 0.1 Cu, 0.4 Fe, 1.0 Mn, 0.1 Si	291	0.594	1
	83	1.11	7
	273	0.840	
Driver Harris Grade A Ni	ca 273	0.615	58
Driver Harris, R-12	ca 273	0.703	58
Cold drawn rod, 99.23 Ni, 0.01 Co, 0.06 Cu, 0.12 C, 0.27 Fe, 0.23 Mn, 0.06 Si, 0.07 S, accuracy = 1%; k/C_p = 1.3269 $\pm$ 0.0012 gm/cm-sec	ca 298	0.572	41

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Nickel (Continued)			
99.25 Ni, 0.01 Co, 0.07 Cu, 0.14 C, 0.11 Fe, 0.26 Mn, 0.07 Si, 0.06 S; error ca 0.06%; $k/C_p = 1.3643 \pm 0.0009$ gm/cm-sec	282	0.589	42
99.98 Ni, d = 8.79, thermal diffusivity = 0.15885 cm^2/sec	298	0.618	25
Filament of "A" Ni wire, 14.86 by 0.00423 cm, accuracy ca 5%	90	0.74	40
	195	0.71	
99.4 Ni, as forged, Brinell hardness = 107	15.12	0.180	12
	18.15	0.221	
	21.50	0.274	
	77.1	0.610	
	93.1	0.661	
99.48 Ni, 0.06 C, 0.22 Mn, 0.02 Si, 0.005 S, 0.05 Cu, 0.14 Fe	273	0.728	59
99.997 Ni, annealed, from Johnson Matthey, read from graph	2	0.50	65
	18	3.40	
	26	3.95	
Palladium			
Pure	291	0.704	1
Commercial	290	0.423	3
Pure	290	0.602	3

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Palladium (Continued)			
Very pure, drawn, untempered, avg of 3 values, $\rho_0 = 9.8 \times 10^{-6}$ ohm-cm	21.7	3.42	7
Same, avg of 2 values	79.41 91.4	0.786 0.736	7
Tempered 2 hr at 360°C, $\rho_0 = 9.77 \times 10^{-6}$ ohm-cm	21.7 80.7	4.08 0.782	7
Moderately pure, untempered, avg of 2 values, $\rho_0 = 9.955 \times 10^{-6}$ ohm-cm	21.8 79.9 91.2	1.76 0.749 0.707	7
99.995 Pd, annealed wire, from Johnson Matthey, read from graph	2 22.5 30.5	0.20 1.45 1.25	65
Platinum			
Very pure	20.4 90 273	3.89 0.761 0.699	1
Pure	291	0.696	1
	290	0.690	3
Polycrystal, very pure, annealed	21 83	3.69 0.778	5
Pure, polycrystal, annealed	21	2.96	5
99.95 Pt	292.7	0.699	7

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Platinum (Continued)			
99.999 Pt, annealed wire, from Johnson Matthey, read from graph	2	4.5	65
	9	13	
	32	2.5	
Potassium			
	278.2	0.979	1
	293.4	0.971	
	330.8	0.908	
Rhodium			
d = 12.50	290	0.878	3
	373	0.803	
Fairly pure, rolled tetragonal wire, annealed 10 min at 1030°C in vacuum	21	23.8	5
	83	2.15	
99.995 Rh, wire, from Johnson Matthey, read from graph	2	3	65
	11	7	
	21	12	
Silver			
99.9 Ag, turned from fine Ag, d = 10.47, ρ (21.0) = 1.675	103	(4.17)	26
	113	4.17	
	123	4.18	
	148	4.20	
	173	4.22	
	198	4.20	
	223	4.17	
	248	4.17	
	273	4.10	
	291	4.07	

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Silver (Continued)			
99.98 Ag	291	4.21	1
	273	4.58	1
Pure, drawn, tempered 2 hr at 350°C, avg of 2 values, ρ_o = 1.50×10^{-6} ohm-cm	21.3 79.4 91.0	9.50 4.39 4.31	7
Pure, single crystals, deformable, $\rho_o = 1.50 \times 10^{-6}$ ohm-cm	78.6 90.8	4.27 4.12	7
Tempered 2 hr at 350°C, ρ_o = 1.49×10^{-6} ohm-cm	79.8 80.0 91.2	4.27 4.52 4.13	7
Commercially pure electrolytic, 0.05286 x 17.63 cm rod	273	4.10	10A
Drawn from spectrographically pure specimen, 0.05059 x 17.47 cm	273	4.03	10A
Small rod	90.16 194.66 273.16	4.24 4.19 4.17	10
Same, after prolonged annealing at 500°C	90.16 194.66 273.16	4.25 4.19 4.17	10
99.99 Ag, polycrystal wire, from Johnson Matthey, read from graph	3 17 21 38	2 6 9 5	65

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Silver (Continued)			
99.999+ Ag, 2 mm dia rod, read from graph	2	0.1	74
	26	2.9	
	140	3.5	
Same, annealed at 650°C, grain dia ca 0.1 mm, read from graph	3	104	74
	7	200	
	19	60	
	30	20	
	60	7	
	140	2	
Same, drawn to 1.16 mm dia, read from graph	2	1.5	74
	20	10.6	
	45	5.8	
	77	4.2	
	140	4.1	
Same, annealed at 650°C, read from graph	2	17	74
	9	110.6	
	23	40	
	55	7	
	140	6	
Sodium			
	33	1.69	3
	73	1.58	
	98	1.51	
	123	1.42	
	148	1.36	
	173	1.28	
	198	1.21	
	223	1.17	
	273	1.40	
	293	1.25	

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Sodium (Continued)			
Traces of Ca and Al between 0.01 and 0.1%, cast in vacuum in soft glass tubes, read from graph; for T less than 15°K, $1/k = 0.42/T + 3.8 \times 10^{-4}(T^2)$	4.0	9.7	68
	8.5	14.2	
	20	5.5	
	38	1.85	
	50	1.45	
	99	1.30	
With a very faint trace of Ag, read from graph; for T less than 15°K, $1/k = 0.06/T + 3.8 \times 10^{-6}(T^2)$	6.0	31.0	68
	14.0	11.5	
	23.0	2.35	
	38	1.85	
	50	1.45	
	99	1.30	
Tantalum			
d = 16.67	290	0.544	3
Drawn wire, 99.9 Ta, aged 2750 hr at 1800 and 2000°K	273	0.36 ± 0.04	20
99.98 Ta, from Johnson Matthey, read from graph	2	0.09	65
	13	0.50	
	21	0.62	
Tellurium			
Less than 0.01% impurities, single crystal, parallel to axis	90	0.022 - 0.31	7
	298	0.017 - 0.019	
Polycrystal, from various sources	90	0.022 - 0.026	7
	298	0.010 - 0.016	

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Thallium			
	313	0.38	3
Purest	80	0.636	7
	273	0.506	
Tin			
Pure, cast, "Kahlbaum", d = 7.28, ρ (13.3) = 10.75	103	0.816	26
	113	0.803	
	123	0.791	
	148	0.761	
	173	0.736	
	198	0.720	
	223	0.703	
	248	0.686	
	273	0.669	
	291	0.657	
	273	0.639	1
	288	0.632	
	288	0.605	
	291	0.640	
Not very pure	273	0.659	44
Titanium			
Commercially pure, error ca 5%, except at 20°K where it is less than 10%	20	0.12	38
	80	0.17	
	90	0.18	
	195	0.21	
	273	0.20	

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Titanium (Continued)			
2.8 Cr, 1 Fe, error ca 5%	80 195 273	0.06 0.10 0.13	38
99.9 Ti, from Associated Electrical Industries, linear in range shown, read from graph	2 23	0.01 0.07	65
Same, annealed, read from graph	2 38	0.018 0.24	65
Tungsten			
	273	1.60	1
"Pladuram"	290	1.99	3
Single crystal, very pure, gas phase separated	21 83	34.3 2.32	5
Single crystal, impure	21 83	1.80 1.83	5
0.001 Co, 0.001 Cr, 0.001 In, 0.001 Os, 0.001 Pt, 0.01 Si, 0.001 Sn, 0.01 Ta, 0.01 V, trace Sc, tetragonal crystal	90.16 194.66 273.16 373.16	1.93 1.69 1.67 1.63	10
Same, hexagonal crystal	90.16 194.66 273.16 373.16	2.14 1.78 1.69 1.63	10

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Tungsten (Continued)			
Wire, 0.00635 cm radius, uncertainty ca 10%	78	2.26	36
	194	1.60	
	273	1.88	
	15.5	23.8	17
	17.1	22.7	
	18.6	20.4	
	21.8	18.2	
Filament heated at 2000°K, then at 2400 and 2800°K (These data reported to 600°K)	240	1.729	21
	244.1	1.720	
	250	1.708	
	260	1.688	
	270	1.669	
	273	1.663	
	280	1.651	
	290	1.633	
	298	1.620	
	300	1.617	
Single crystal, very pure	15.33	84.7	45
	15.59	82.0	
	15.75	81.3	
	16.68	70.9	
	16.69	74.6	
	17.24	68.5	
	17.27	67.6	
	17.69	66.2	
	17.85	65.8	
	19.03	59.5	
	19.20	57.8	
	19.55	57.1	

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Tungsten (Continued)			
Single crystal, very pure (Continued)	20.17	51.8	45
	20.74	50.5	
	21.58	46.5	
	57.29	3.41	
	57.67	3.38	
	66.35	2.92	
	67.88	2.88	
	70.98	2.78	
	75.53	2.66	
	76.14	2.62	
	83.72	2.48	
	88.38	2.44	
Wire, highest purity available, aged 370 hr at 2400 to 2600°C	77.4	1.86	20
	90.2	1.82	
	273.2	1.70	
Same, aged at 2300°C	77.36	1.93	20
	90.2	1.87	
	273.2	1.70	
99.99 W, annealed, from Johnson Matthey, read from graph	2	0.50	65
	28	3.70	
	44	3.30	
Uranium			
	ca 298	0.268	30
Read from graph	2	0.03	65
	10	0.10	
	21	0.16	

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Uranium (Continued)			
Normal, uncertain purity, accuracy ca 5%, read from graph	22	0.12$\underline{5}$	77
	44	0.15$\underline{9}$	
	80	0.20$\underline{5}$	
	110	0.23$\underline{0}$	
	200	0.25$\underline{1}$	
	273	0.26$\underline{4}$	
Zinc			
Pure, cast, redistilled, d = 7.10, $\rho = 6.34 \times 10^{-6}$ ohm-cm at 18.8°C	103	1.17	26
	113	1.16	
	123	1.15	
	148	1.13	
	173	1.13	
	198	1.12	
	223	1.12	
	248	1.12	
	273	1.12	
	291	1.12	
Pure	291	1.11	1
	288	1.06	1
Very pure, fused in quartz in vacuum, solidified in water	83	1.25	5
	273	1.25	
Single crystal, 0.005 Fe, 0.0018 Cd, 0.0002 other impurities	23	1.5$\underline{9}$	5
	73	1.5$\underline{1}$	
	123	1.4$\underline{4}$	
	173	1.3$\underline{8}$	
	223	1.3$\underline{2}$	
	273	1.2$\underline{7}$	
	323	1.2$\underline{3}$	

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Zinc (Continued)			
Single crystals	23	1.60	5
	48	1.56	
	73	1.51	
	173	1.38	
	273	1.27	
Polycrystal, 0.005 Fe, 0.0018 Cd, 0.0002 other impurities, open air fused	23	1.39	5
	73	1.30	
	123	1.22	
	173	1.17	
	223	1.12	
	273	1.07	
	323	1.04	
Same, fused in vacuum	73	1.38	5
	123	1.31	
	173	1.24	
	223	1.18	
	273	1.13	
	323	1.10	
Polycrystal, very pure	23	1.43	5
	73	1.36	
	173	1.24	
	273	1.14	
Single crystal, pure, undeformed, parallel to hexagonal axis	21	7.07	7
	83	1.32	
	293	1.24	
Same, perpendicular to hexagonal axis	21	5.65	7
	83	1.37	
	293	1.24	

TABLE I (Continued)

Thermal Conductivities of Pure Metals

	T°K	k	Ref.
Zinc (Continued)			
99.997 Zn (by difference), 0.003 Fe, $k/C_p = 2.832 \pm 0.004$ $(\text{gm-cm-sec})^{-1}$, error ca 0.13%	273	1.08	43
99.9995 Zn, polycrystal, Hilger H. S. brand, read from graph	3	6.8	65
	10	15	
	22	6	
Zirconium			
ca 98 Zr, annealed, from Johnson Matthey, read from graph	2.5	0.03	65
	15	0.18	
	27	0.28	

TABLE II

Thermal Conductivities of Non-Ferrous Alloys

	T°K	k	Ref.
Aluminum Alloys			
Aluminum-Copper			
Chill casting, 8 Cu, avg	87	0.887	8
of 2 values	273	1.32	
15 Cu, chill casting	87	0.904	8
	273	1.48	
3-5 Cu, 0.5 Mg, pressed	87	0.887	8
and tempered	273	1.60	
Duraluminum, as stamped,	15.83	0.240	12
4.10 Cu, 0.57 Mg, 0.42 Fe,	17.04	0.263	
94.0 Al	17.91	0.272	
	19.79	0.294	
	20.61	0.302	
	75.7	0.909	
	84.1	0.971	
Aluminum-Magnesium			
8 Mg	87	0.728	8
	273	1.00	
Same, thermally treated	87	0.766	8
	273	1.05	
12 Mg	87	0.561	8
	273	0.774	
14 Mg, thermally treated	87	0.435	8
	273	0.690	
Aluminum-Silicon			
ca 20 Si, chill casting,	87	1.20	8
"Alusil"	273	1.59	

TABLE II (Continued)

Thermal Conductivities of Non-Ferrous Alloys

			T°K	k	Ref.
Aluminum Alloys (Continued)					
Aluminum-Copper-Nickel					
ca 4 Cu, 2 Ni, 1.5 Mg,			87	1.12	8
"Y-alloy"			273	1.62	
Same, thermally treated			87	1.38	8
			273	1.53	
Bismuth Alloys					
Bismuth-Antimony					
Cast: %Bi	%Sb	83°K	196°K	273°K	2
100	0	0.261	0.108	0.102	
91	9	0.0669	0.0602	0.0657	
89	11	0.0506	0.0448	0.0548	
87	13	0.0552	0.0515	0.0632	
80	20	0.0561	0.0531	0.0636	
50	50	0.0732	0.0745	0.0820	
30	70	0.0862	0.0883	0.0979	
0	100	0.443	0.263	0.225	
Pressed powder. d = ca 1% less than cast					2
%Bi	%Sb	83°K	196°K	273°K	
100	0	0.208	-	0.0812	
95	5	0.0581	-	0.0598	
93	7	-	-	0.0485	
89	11	0.160	-	0.0904	
87	13	0.0933	-	0.0878	
0	100	-	0.137	0.121	
Bismuth-Lead-Tin					
50 Bi, 25 Pb, 25 Sn, eutectic			14.7	0.0418	18
			16.1	0.0448	
			17.9	0.0485	
			20.1	0.0532	
			82	0.0847	
			276	0.164	

TABLE II (Continued)

Thermal Conductivities of Non-Ferrous Alloys

	T°K	k	Ref.
<u>Bismuth Alloys (Continued)</u>			
Bismuth-Lead-Tin-Cadmium (Lipowitz alloy)			
ca 50 Bi, 25 Pb, 14 Sn, 11 Cd	103	(0.176)	26
d = 9.66, ρ (19.6) = 47.5,	113	0.176	
melting point = 65°C	123	0.176	
	148	0.176	
	173	0.176	
	198	0.180	
	223	0.180	
	248	0.184	
	273	0.184	
	291	0.184	
Same, Wood's alloy			
ca 50 Bi, 25 Pb, 12.5 Sn, 12.5 Cd	280	0.133	2

<u>Cadmium Alloys</u>

Cadmium-Antimony

%Cd	%Sb	83°K	194°K	273°K	Ref.
					2
100	0	1.23	1.02	1.02	
66.7	33.3	0.140	0.118	0.112	
50	50	0.0530	0.0265	0.0217	
48.3	51.7	0.0369	0.0205	0.0132	
33.3	66.7	0.0250	0.0165	0.0125	
0	100	0.248	0.186	0.159	

<u>Copper Alloys</u>

	T°K	k	Ref.
Copper-Gold			
95.3 Au, 4.7 Cu, polycrystal,	21.8	0.306	8
untempered, avg of 2 values,	79.6	$0.82\overline{0}$	
ρ = 3.93	91.4	0.891	

TABLE II (Continued)

Thermal Conductivities of Non-Ferrous Alloys

	T°K	k	Ref.
Copper Alloys (Continued)			
Copper-Gold (Continued)			
9.0 Cu, 91.0 Au, polycrystal, untempered, ρ = 5.94	22.4	0.159	8
	79.5	0.456	
	91.3	0.506	
26.4 Cu, 73.6 Au, polycrystal, untempered	79.6	0.228	8
	91.5	$0.25\overline{\underline{8}}$	
Same, tempered ca 4 hr at 365°C, ρ = 10.9	22.2	0.841	8
49.9 Cu, 50.1 Au, polycrystal, quenched from 800°C, ρ = 13.2	85.9	0.193	8
Same, tempered ca 22 hr at 360°C, ρ = 3.97	85.1	1.28	8
Same, tempered 30 hr more at 345°C, ρ = 4.48	80.9	0.849	8
	91.7	0.891	
Same, tempered 3 hr more at 325°C, ρ = 4.07	79.1	1.03	8
	91.3	1.08	
Same, held 2 hr at 800°C, then quenched	79.3	0.227	8
	91.4	$0.23\overline{\underline{5}}$	
Same, supposedly tempered by dip brazing, better ordered	22.2	0.0887	8
	79.1	0.259	
Same, ordered at 320-330°C, ρ = 4.09	21.5	0.469	8
	81.4	1.01	

TABLE II (Continued)

Thermal Conductivities of Non-Ferrous Alloys

	T°K	k	Ref.
Copper Alloys (Continued)			
Copper-Gold (Continued			
75 Cu, 25 Au, polycrystal, quenched from 800°C	80.9 90.8	0.332 0.355	8
Same, tempered 20 hr at ca 400°C	87.4	0.627	8
Same, tempered 30 hr more at 360°C, $\rho = 5.42$	79.8 91.7	0.619 0.661	8
Same, tempered 2 hr more at 820°C, $\rho = 11.5$	22.5 80.1 91.6	0.0966 0.226 0.248	8
Same, ordered 30 hr at 320-330°C	21.7 80.5	0.241 0.586	8
90.3 Cu, 9.7 Au, polycrystal, untempered, $\rho = 6.45$	22.1 80.2 92.7	0.146 0.401 0.448	8
95.5 Cu, 4.5 Au, polycrystal, untempered, $\rho = 3.83$	21.7 79.5 91.0	0.246 0.686 0.841	8
Copper-Manganese			
Manganin	291	0.217	2
70 Cu, 30 Mn, technical alloy, remelted in electric furnace, 48 grains per cm	80 273	0.0607 0.0904	8

TABLE II (Continued)

Thermal Conductivities of Non-Ferrous Alloys

	T°K	k	Ref.
Copper Alloys (Continued)			
Copper-Manganese (Continued)			
Same, 112 grains per cm	80	0.0858	8
	273	0.125	
70 Cu, 30 Mn, reguline bloom,	80	0.0661	8
ca 200 grains per cm	273	0.120	
Same, ca 500 grains per cm	80	0.0849	8
	273	0.136	
Copper-Nickel			
60 Cu, 40 Ni, constantan	291	0.268	2
54 Cu, 46 Ni, d = 8.89	291	0.202	2
99 Cu, 1 Ni, drawn rod	21	0.619	6
	83	1.93	
90 Cu, 10 Ni, annealed,	3.33	0.00796	11
1/8-in o.d.	4.21	0.0120	
	14.1	0.0964	
	16.7	0.123	
	19.7	0.157	
	64.0	0.388	
	78.0	0.378	
Same, cold worked, rolled	3.03	0.00580	11
from 0.25-in to 0.14-in dia	3.61	0.00734	
before machining to size	4.21	0.00917	
	4.40	0.0103	
	14.07	0.0601	
	17.0	0.0825	
	19.7	0.104	
	71.3	0.343	
	76.2	0.358	

TABLE II (Continued)

Thermal Conductivities of Non-Ferrous Alloys

	T°K	k	Ref.
Copper Alloys (Continued)			
Copper-Nickel (Continued)			
Same, severely cold worked,	3.63	0.00735	11
rolled from 0.5-in square cross	4.20	0.00892	
section to 0.22-in by 0.24-in	4.72	0.0108	
before machining	14.1	0.0587	
	17.2	0.0786	
	19.4	0.0986	
	64.0	0.326	
	70.6	0.333	
	78.7	0.348	
90 Cu, 10 Ni, single crystal,	3.45	0.00980	11
1/8-in o.d., made by remelting	4.80	0.0173	
a piece of the same forged bar	14.2	0.1036	
as used for the above samples in	17.0	0.135	
a graphite furnace in vacuum and	20.5	0.170	
cooling slowly	64.5	0.350	
	73.0	0.361	
	79.3	0.357	
80 Cu, 20 Ni, tube 5 mm o.d. by	1.89	0.00281	14
3 mm i.d., from Johnson Matthey,	2.40	0.00372	
avg grain size 0.011 mm in each	2.86	0.00485	
direction	3.02	0.00549	
	3.38	0.00590	
	3.60	0.00677	
	3.88	0.00725	
	4.05	0.00784	
	4.23	0.00841	
	4.45	0.00908	
	16.3	0.0799	
	21.9	0.127	

TABLE II (Continued)

Thermal Conductivities of Non-Ferrous Alloys

	T°K	k	Ref.
Copper Alloys (Continued)			
Copper-Nickel (Continued)			
70 Cu, 30 Ni, 4.1 mm o.d. by	10	0.0209	15
0.8 mm wall thickness, from	15	0.0356	
Yorkshire Copper Works, Ltd.	20	0.0502	
Also: $k = a + bT$, from ca 5 to 25°K where $a = -2.0$, $b = 0.7$, units are millical/(cm-sec-deg)			
70 Cu, 30 Ni	366	0.297	57
Constantan, 60 Cu, 40 Ni,	3.5	0.005	72
specimen was 317 enameled 36	7.5	0.020	
gauge wires in parallel, read	12	0.050	
from graph	25	0.100	
	60	0.185	
	100	0.19	
Constantan, 55 Cu, 45 Ni, pure	80	0.195	6, 8
electrolytic metals, remelted,	273	0.240	
rolled from rod, deformed			
Same, homogenized at glowing	80	0.203	6, 8
heat for several days, recrystal-	273	0.237	
lized by rolling on edge, 51 grain			
boundaries per cm			
Same, 68 grain boundaries per cm	80	0.199	6, 8
	273	0.230	
Same, same treatment then	80	0.213	6, 8
annealed 1.5 hr at 650°C,	273	0.253	
475 boundaries per cm			

TABLE II (Continued)

Thermal Conductivities of Non-Ferrous Alloys

			T°K	k	Ref.
Copper Alloys (Continued)					
Copper-Nickel (Continued)					
Same, 628 grain boundaries			80	0.205	6, 8
per cm			273	0.253	
55 Cu, 45 Ni, (Advance)			ca 273	0.228	58
Strongly deformed specimen			80	0.157	6, 8
			273	0.231	
%Ni	%Mn	%Fe			
100 (electrolytic)			78	0.996	31
95.35	0.26	0.03	78	0.464	
90.98	0.13	0.04	78	0.333	
86.14	0.10	0.05	78	0.269	
78.20	0.05	0.05	78	0.213	
69.56	0.05	0.03	78	0.182	
59.35	0.04	0.07	78	0.150	
49.75	0.05	0.03	78	0.161	
39.84	0.02	0.04	78	0.178	
29.89	0.03	0.03	78	0.201	
19.83	0.04	0.02	78	0.234	
13.84	trace	0.11	78	0.280	
9.47		0.14	78	0.351	
3.67		0.09	78	0.0703	
1.03		0.03	78	0.175	
Electrolytic copper			78	5.51	
Monel, 28 Cu, 70 Ni, 2 Fe			ca 273	0.348	58
Monel metal, 30.2 Cu, 67 Ni,			15.17	0.0444	12
as forged			18.16	0.0553	
			21.47	0.0661	
			31.8	0.0977	
			76.0	0.137	
			93.1	0.146	

TABLE II (Continued)

Thermal Conductivities of Non-Ferrous Alloys

	ΔT°K	T°K	k	Ref.
Copper Alloys (Continued)				
Copper-Nickel (Continued)				
Monel tubing,	0.112	4.2	0.00526	11
commercial	12.2	63.3	0.137	
hard drawn, 0.125-in	11.45	77.3	0.146	
o.d. by 0.006-in wall thickness	10.9	77.3	0.153	
Same specimen, different	0.178	4.2	0.00533	11
run	0.377	14.0	0.0264	
	0.492	20.4	0.0412	
	3.57	73.7	0.138	
	3.71	77.0	0.125	
	2.29	77.0	0.141	
Monel tubing, annealed	0.077	2.55	0.00396	11
0.125-in o.d. by 0.0105-	0.16	4.25	0.00911	
in wall thickness	0.45	14.0	0.0464	
	0.37	20.5	0.0745	
	1.28	54.0	0.140	
	1.80	63.0	0.144	
	3.00	63.7	0.147	
	2.77	68.4	0.164	
	2.71	77.0	0.168	
Monel rod, hard drawn,	0.0654	2.6	0.00216	11
0.125-in o.d.	0.0510	2.7	0.00218	
	0.14	4.2	0.0045	
	0.16	10.1	0.0131	
	0.70	20.4	0.0406	
	0.44	20.6	0.0428	
	1.7	51.6	0.0855	
	2.8	59.0	0.112	
	2.7	63.3	0.111	
	2.3	75.5	0.128	
	2.15	77.0	0.148	

TABLE II (Continued)

Thermal Conductivities of Non-Ferrous Alloys

	T°K	k	Ref.
Copper Alloys (Continued)			
Copper-Palladium			
93.6 Cu, 6.4 Pd, polycrystal,	22.2	0.130	8
untempered, ρ = 6.82	80.0	0.431	
55 Cu, 45 Pd, annealed,	80.1	0.657	8
ρ = 5.32	86.6	.682	
Same, annealed in vacuum 2 hr,	21.5	0.0690	8
quenched, ρ = 36.4	80.4	0.0996	
	92.0	0.103	
Same, ordered 30 hr at 320-	21.8	0.265	8
330°C, ρ = 5.25	80.2	.623	
49.9 Cu, 50.1 Pd, annealed,	21.6	0.0724	8
ρ = 36.8	82.8	0.105	
14.5 Cu, 85.5 Pd, polycrystal,	21.8	0.0384	8
untempered, ρ = 28.05	80.3	0.128	
	91.31	0.134	
Copper-Silver			
97 Cu, 3 Ag, untempered	21	3.57	6
	83	3.57	
Same, tempered 3 hr at 390°C	23	6.19	6
	83	4.06	

TABLE II (Continued)

Thermal Conductivities of Non-Ferrous Alloys

	T°K	k	Ref.
Copper Alloys (Continued)			
Copper-Zinc			
%Cu %Zn Microstructure	78°K	273°K	
100 (electrolytic)	5.505	3.97	32
95.48 4.54	1.28	2.19	
92.82 7.18	1.05	1.87	
86.87 13.13	0.807	1.60	
82.58 17.42	0.7137	1.48	
79.73 20.27	0.6886	1.44	
75.44 24.56	0.6225	1.34	
70.00 30.00	0.5304	1.21	
64.05 35.95	0.5099	1.14	
62.30 37.70	0.5480	1.19	
59.93 40.07	0.6463	1.28	
55.62 44.38	0.887	1.41	
51.09 48.91	1.47	1.61	
Red brass, 82 Cu, 18 Zn, fine grains, cross sectional area = 0.006 sq cm	90	0.669	4
	273	1.25	
Same, large grains, cross sectional area = 0.11 sq cm	90	0.648	4
	273	1.30	
ca 70 Cu, 30 Zn, d = 8.44, ρ (21.5) = 6.57	103	(0.732)	26
	113	0.757	
	123	0.778	
	148	0.837	
	173	0.891	
	198	0.941	
	223	0.983	
	248	1.02	
	273	1.06	
	291	1.09	

TABLE II (Continued)

Thermal Conductivities of Non-Ferrous Alloys

	T°K	k	Ref.
Copper Alloys (Continued)			
Copper-Manganese-Nickel			
ca 84 Cu, 12 Mn, 4 Ni,	103	(0.142)	26
d = 8.42, ρ (17.7) =	113	0.146	
44.6 ohm/cm (x 10^{-6})	123	0.146	
Manganine	148	0.155	
	173	0.163	
	198	0.172	
	223	0.180	
	248	0.192	
	273	0.209	
	291	0.218	
Copper-Nickel-Zinc			
63 Cu, 20 Ni, 17 Zn, from	10	0.026	15
Messrs. Henry Righton, 10 mm	15	0.0485	
o.d. by 0.1 mm wall thickness;	20	0.071	
Also: k = a + bT, from ca 5 to 25°K, where a = -4.9, b = 1.1, units are millical/(cm-sec-deg)			
"Neusilber", 64 Cu, 16 Ni,	3.0	0.009	66
20 Zn	5.0	0.018	
	10.0	0.058	
	15.0	0.103	
	20.0	0.145	
German silver, ca 62 Cu,	103	(0.176)	26
15 Ni, 22 Zn, d = 8.42,	113	0.180	
ρ (21.2) = 39.9, see	123	0.184	
"Platinoid" below	148	0.188	
	173	0.197	
	198	0.205	
	223	0.213	
	248	0.226	
	273	0.234	
	291	0.247	

TABLE II (Continued)

Thermal Conductivities of Non-Ferrous Alloys

	T°K	k	Ref.
Copper Alloys (Continued)			
Copper-Nickel-Zinc (Continued)			
"Platinoid", ca 62 Cu,	103	(0.163)	26
15 Ni, 22 Zn, d = 8.66,	113	0.167	
ρ (21.2) = 34.4, see	123	0.172	
German silver above	148	0.180	
	173	0.188	
	198	0.201	
	223	0.213	
	248	0.230	
	273	0.243	
	291	0.251	
German silver, 47 Cu, 9 Ni,	2	0.003	72
41 Zn, 2 Pb, mean grain dia =	5	0.010	
ca 0.02 mm, read from graph	16	0.050	
	30	0.10	
	60	0.17	
	100	0.18	
"Silberbronze", 46 Cu,	5.0	0.0105	66
13 Ni, 41 Zn	10.0	0.0250	
	15.0	0.048	
	20.0	0.056	
Gold Alloys			
Gold-Palladium			
91.1 Au, 8.9 Pd, tempered 2 hr	21.8	0.232	8
at 800°C, ρ = 5.44	82.9	0.548	
83.0 Au, 17.0 Pd, tempered	21.9	0.148	8
2 hr at 800°C, ρ = 9.10	83.0	0.309	

TABLE II (Continued)

Thermal Conductivities of Non-Ferrous Alloys

	T°K	k	Ref.
Gold Alloys (Continued)			
Gold-Palladium (Continued)			
45.0 Au, 55.0 Pd, tempered	22.1	0.0544	8
2 hr at 800°C, ρ = 27.1	80.2	0.115	
	91.5	0.129	
Gold-Silver			
75 Au, 25 Ag, single crystal,	22.2	0.159	8
ρ = 8.69	80.5	0.129	
	91.6	0.339	
50 Au, 50 Ag, single crystal,	22.0	0.123	8
ρ = 10.8	79.3	0.238	
	91.2	0.262	
25 Au, 75 Ag, single crystal,	22.5	0.140	8
ρ = 8.57	80.2	0.303	
	92.0	0.334	
0.37 Au, 99.63 Ag, ρ = 1.63	22.2	2.94	8
	82.5	3.49	
	91.7	3.56	
Lead Alloys			
Lead-Indium			
99 atom % Pb	14.8	0.149	18
	16.1	0.158	
	17.9	0.160	
	20.4	0.165	
	81	0.263	

TABLE II (Continued)

Thermal Conductivities of Non-Ferrous Alloys

	T°K	k	Ref.
Lead Alloys (Continued)			
Lead-Indium (Continued)			
50 atom % Pb	14.9	0.0242	18
	16.3	0.0267	
	18.0	0.0293	
	20.4	0.0326	
	69	0.0813	
	83	0.0980	
	278	0.202	
8.6 atom % Pb	14.9	0.0602	18
	16.3	0.0676	
	18.1	0.0725	
	20.1	0.0775	
	22.7	0.0855	
	27	0.101	
	70	0.216	
	81	0.248	
	174	0.388	
Lead-Tin			
56 Pb, 44 Sn	14.7	0.249	18
	17.1	0.276	
	18.9	0.287	
	20.8	0.294	
	66	0.377	
	70	0.483	
Lead-Thallium			
34 Pb, 66 Tl, large grains, slowly cooled	83	0.127	8
	273	0.219	
Same, rapidly cooled, fine grains	83	0.143	8
	273	0.232	

TABLE II (Continued)

Thermal Conductivities of Non-Ferrous Alloys

	T°K	k	Ref.
<u>Magnesium Alloys</u>			
Magnesium-Aluminum			
94 Mg, 6 Al	87	0.602	6, 8
	273	0.799	
92 Mg, 8 Al	87	0.418	6, 8
	273	0.648	
88 Mg, 12 Al	87	0.335	6, 8
	273	0.586	
Magnesium-Cadmium			
92 Mg, 8 Cd, chill casting	87	0.130	6, 8
	273	0.141	
Magnesium-Cerium			
92 Mg, 8 Ce, chill casting	87	1.06	6, 8
	273	1.25	
88 Mg, 12 Ce, chill casting	87	0.807	6, 8
	273	1.03	
Magnesium-Copper			
92 Mg, 8 Cu, chill casting	87	0.878	6, 8
	273	1.25	
85 Mg, 15 Cu, chill casting	87	1.51	8
	273	1.54	
97.6 Mg, 2.4 Cu, annealed in vacuum	293.5	1.39	8
93.7 Mg, 6.3 Cu, annealed in vacuum	297.4	1.31	8

TABLE II (Continued)

Thermal Conductivities of Non-Ferrous Alloys

	T°K	k	Ref.
Magnesium Alloys (Continued)			
Magnesium-Manganese			
99.5 Mg, 0.5 Mn, chill casting	87	1.34	6, 8
	273	1.60	
99.2 Mg, 0.8 Mn, chill casting	87	1.22	6, 8
	273	1.58	
98 Mg, 2.0 Mn, chill casting	87	0.674	6, 8
	273	1.18	
96.46 Mg, 3.54 Mn, chill casting	87	0.565	6, 8
	273	1.02	
Magnesium-Silicon			
99.3 Mg, 0.7 Si, chill casting	87	1.10	6, 8
	273	1.47	
98.5 Mg, 1.5 Si, chill casting	87	0.950	6, 8
	273	1.40	
Magnesium-Zinc			
97.9 Mg, 2.1 Zn	299.0	1.25	8
93.9 Mg, 6.1 Zn	298.7	1.09	8
95.5 Mg, 4.0 Zn, 0.5 Cu, "Elektron"	298.8	1.14	8
92 Mg, 8 Zn	87	0.887	6, 8
	273	1.19	

TABLE II (Continued)

Thermal Conductivities of Non-Ferrous Alloys

		T°K	k	Ref.
Magnesium Alloys (Continued)				
Magnesium-Aluminum-Silicon				
6 Al, 2 Si		87	0.481	6, 8
		273	0.686	
8 Al, 2 Si		87	0.376	6, 8
		273	0.607	
10 Al, 2 Si		87	0.289	6, 8
		273	0.552	
12 Al, 2 Si		87	0.276	6, 8
		273	0.535	
Magnesium-Copper-Silicon				
20 Cu, 3 Si		87	0.891	8
		273	1.08	
Nickel Alloys				
Nickel-Chromium				
80 Ni, 20 Cr, Nichrome IV		ca 273	0.150	58
80 Ni, 20 Cr		309.1	0.131	8
76.98 Ni, bal Cr, Nichrome, forged		78	0.092	33
		273	(0.125)	
	ΔT°K			
Inconel tubing, hard drawn, 0.125-in by 0.0105-in walls	0.060	2.6	0.00108	11
	0.240	4.2	0.00306	
	0.129	4.2	0.00265	
	0.44	9.6	0.0087	
	0.45	14.0	0.0143	
	0.64	20.4	0.0248	
	4.0	63.3	0.0744	
	4.8	73.4	0.0866	
	3.0	77.0	0.0910	

TABLE II (Continued)

Thermal Conductivities of Non-Ferrous Alloys

	$\Delta T°K$	$T°K$	k	Ref.
Nickel Alloys(Continued)				
Nickel-Chromium (Continued)				
Inconel tubing, annealed,	0.078	2.55	0.00200	11
0.126-in by 0.0105-in	0.19	4.25	0.00483	
walls	0.51	14.0	0.0270	
	0.48	20.5	0.0407	
	0.73	20.5	0.0415	
	0.80	22.1	0.0470	
	2.3	54.0	0.0963	
	3.2	63.3	0.100	
	5.0	63.7	0.104	
	3.1	68.4	0.0966	
	4.7	77.0	0.110	
Inconel rod, hot rolled,	0.06	2.59	0.00196	11
1/8-in o.d.	0.16	4.25	0.00489	
	0.48	14.0	0.0277	
	2.4	58.0	0.091	
	4.1	63.0	0.0935	
	2.3	63.3	0.0935	
	4.0	63.3	0.0962	
	4.0	70.6	0.0965	
	3.8	76.2	0.100	
Same, different run	0.045	2.57	0.00213	
	0.20	4.25	0.00517	
	0.13	4.25	0.00493	
	0.20	10.1	0.0168	
	0.46	14.0	0.0297	
	2.2	58.7	0.0997	
	2.2	59.2	0.0997	
	2.0	77.8	0.107	

TABLE II (Continued)

Thermal Conductivities of Non-Ferrous Alloys

	ΔT°K	T°K	k	Ref.
Nickel Alloys (Continued)				
Nickel-Chromium-Iron				
Chroman B2Mo, 61.4 Ni,	0.56	3.9	0.0026	60
18.5 Cr, 14.5 Fe, 3 Mn,	6.43	70	0.046	
2 Mo, 0.6 Si, softened	3.05	88	0.12	
sheet, 0.1 mm thick				
Nichrome, 62 Ni, 12 Cr, 26 Fe		ca 273	0.136	58
Nickel-Chromium-Iron-Molybdenum				
60 Ni, 15 Cr, 16 Fe, 7 Mo,		3.0	0.00150	66
"Contracid"		5.0	0.0030	
		10.0	0.0060	
		15.0	0.0120	
		20.0	0.0155	
Titanium Alloy				
Titanium-Manganese-Aluminum				
91.17 Ti, 4.7 Mn, 3.99 Al,		18	0.0142	76
0.14 C, Titanium alloy RC-		24	0.0201	
130-B made by Rem Cru		42	0.0293	
Titanium, Inc., read from		73	0.0418	
graph		120	0.0544	
		160	0.0627	
		210	0.0669	
		250	0.0753	
		273	0.0795	

TABLE III

Thermal Conductivities of Ferrous Alloys

	T°K	k	Ref.
Aluminum Steel			
4.11 Al, 0.03 C, 0.13 Si, 0.006 S, 0.017 P, 0.08 Mn, heated to 800°C, cooled in furnace	14.97	0.0218	12
	17.71	0.0269	
	21.50	0.0368	
	76.6	0.118	
	93.1	0.142	
Carbon Steel			
ca 1 C, d = 7.84, ρ (22.1) = 18.71	103	(0.473)	26
	113	0.473	
	123	0.473	
	148	0.473	
	173	0.477	
	198	0.481	
	223	0.485	
	248	0.485	
	273	0.485	
	291	0.481	
0.4 C, 0.20 to 0.35 Si, 0.50 to 0.70 Mn, less than 0.03 S, less than 0.03 P	3.0	0.0075	66
	5.0	0.0165	
	10.0	0.0330	
	15.0	0.065	
	20.0	0.100	
0.14 C, 0.08 Si, 0.07 Mn, heated to 800°C, cooled in furnace	15.00	0.154	12
	17.16	0.186	
	19.22	0.209	
	21.66	0.244	
	29.9	0.306	
	76.1	0.523	
	93.0	0.568	

TABLE III (Continued)

Thermal Conductivities of Ferrous Alloys

	T°K	k	Ref.
Chromium, Nickel and Stainless Steels			
13.57 Cr, 0.36 C, 0.22 Si,	15.28	0.0204	12
0.13 Mn, cooled in furnace	18.37	0.0268	
	21.53	0.0339	
	75.4	0.118	
	93.0	0.144	
Same, heated to 950°C, quenched	15.30	0.0168	12
in oil, reheated to 450°C,	18.29	0.0212	
cooled in air	21.38	0.0264	
	75.8	0.099	
	92.4	0.114	
57.5 Ni, 1.31 Mn, 0.34 C,	15.12	0.0351	12
0.14 Si; A.M.F., as forged	18.20	0.0426	
	21.31	0.0510	
	76.4	0.132	
	92.9	0.153	
36.17 Ni, 0.92 Mn, 0.09 Si,	15.45	0.0137	12
0.16 C, heated to 1050°C,	18.11	0.0158	
quenched in water	20.08	0.0181	
	20.41	0.0186	
	76.8	0.0714	
	87.0	0.0787	
31.4 Ni, 0.82 Mn, 0.70 C,	15.70	0.0152	12
heated to 800°C, cooled	18.63	0.0188	
in furnace	21.93	0.0225	
	77.7	0.0826	
	95.6	0.1028	

TABLE III (Continued)

Thermal Conductivities of Ferrous Alloys

	T°K	k	Ref.
Chromium, Nickel and Stainless Steels (Continued)			
24.30 Ni, 6.05 Mn, 1.18 C, heated to 1050°C, quenched in water	15.35	0.0120	12
	18.09	0.0146	
	21.90	0.0178	
	77.5	0.0548	
	93.6	0.0641	
3.00 Ni, 0.98 Cr, 0.80 Mn, 0.28 C, oil hardened, tempered 830/600°C	78	0.180	33
	273	(0.335)	
2.61 Ni, 0.49 Cr, 0.27 C, 0.11 Si, 0.029 P, 0.45 Mn, 0.75 Mo, heated to 850°C, quenched in oil, reheated to 650°C, quenched in water	15.16	0.0408	12
	15.60	0.0410	
	17.69	0.0474	
	19.99	0.0581	
	20.99	0.0619	
	21.26	0.0637	
	74.0	0.215	
	75.9	0.222	
	85.2	0.242	
	87.1	0.247	
1.92 Ni, 0.72 Mn, 0.21 Si, 0.14 C, heated to 800°C, cooled in furnace	15.12	0.0553	12
	17.90	0.0725	
	21.93	0.0877	
	76.4	0.267	
	94.6	0.307	
	179.8	0.379	
SS, 18.45 Cr, 8.20 Ni, 0.04 C, 0.20 Ti, bal Fe, forged	78	0.0878	33
	273	(0.15)	

TABLE III (Continued)

Thermal Conductivities of Ferrous Alloys

	ΔT°K	T°K	k	Ref.
Chromium, Nickel and Stainless Steels (Continued)				
SS, 18.80 Cr, 8.10 Ni, 0.12 C,		15.25	0.0129	12
0.43 Si, 0.24 Mn, heated to		17.90	0.0156	
1150°C, quenched in water		21.11	0.0187	
		76.3	0.0714	
		92.8	0.0814	
SS, 17.95 Cr, 8.30 Ni, 0.04 C,		78	0.0941	33
bal Fe, forged		273	(0.15)	
SS, 17.80 Cr, 9.19 Ni, 0.04 C,		78	0.0950	33
3.00 Mo, 1.50 Cu, bal Fe, forged		273	(0.15)	
SS, 18-8 (This data from an article		2	0.0012	63
on the thermal conductivity of		5	0.0035	
polycrystalline solids;		10	0.008	
source of data not specifically		20	0.02	
indicated)		50	0.05	
		100	0.08	
		Room	0.14	
SS type 303, 1/8-in dia rod	0.108	4.2	0.00247	11
	0.098	4.2	0.00253	
	0.38	10.1	0.00663	
	0.079	20.4	0.0199	
	1.04	20.6	0.0220	
	2.9	56.9	0.0669	
	2.8	58.0	0.0657	
	2.8	59.7	0.0667	
	2.6	63.3	0.0719	
	5.5	66.8	0.0733	
	2.15	77.0	0.0843	

TABLE III (Continued)

Thermal Conductivities of Ferrous Alloys

	T	T°K	k	Ref.
Chromium, Nickel and Stainless Steels (Continued)				
Same, different run	0.059	2.59	0.00125	11
	0.15	4.25	0.00240	
	0.46	10.1	0.00693	
	1.2	19.4	0.0198	
	3.2	58.3	0.0664	
	3.1	59.5	0.0672	
	2.6	77.8	0.0823	
SS type 304, read from graph		63	0.0627	76
		80	0.0711	
		100	0.0837	
		190	0.117	
		273	0.134	
SS type 316, read from graph		22	0.0243	76
		80	0.0837	
SS type 347, (Cb stabilized),	0.17	4.25	0.00234	11
1/8-in dia rod	0.18	4.25	0.00234	
	0.52	14.0	0.0117	
	3.5	58.5	0.0638	
	3.4	63.2	0.0660	
	3.4	63.3	0.0670	
	3.1	70.7	0.0732	
	2.9	76.2	0.0772	
SS, austenitic 18-8, Ti stabilized,		4	0.002	72
18.9 Cr, 7.9 Ni, 1 Ti, 0.7 Si,		7	0.005	
ca 0.1 C, 3 rods of 2 mm dia,		11	0.010	
austenite grains ca 0.01 mm dia,		20	0.020	
with some ferrite grains (ca		48	0.050	
0.002 mm dia) precipitated at		95	0.080	
the austenite boundaries, read				
from graph				

TABLE III (Continued)

Thermal Conductivities of Ferrous Alloys

	T°K	k	Ref.
Chromium, Nickel and Stainless Steels (Continued)			
SS, 3.2 mm o.d. by 0.4 mm wall thickness, from Accles and Pollock	10	0.0071	15
	15	0.011	
	20	0.015	
Also: $k = a + bT$, ca 5 to 25°K; $a = -0.12$, $b = 0.18$, units millical/(cm-sec-deg)			
SS, "Era/ATV", 27.30 Ni, 14.60 Cr, 3.50 W, 1.34 Mn, 1.62 Si, 0.44 C, heated to 1000°C, quenched in water	15.30	0.0114	12
	18.30	0.0143	
	21.78	0.0179	
	76.9	0.0551	
	93.4	0.0650	
SS, 26.56 Ni, 14.13 Cr, 2.21 W, 1.06 Mn, 0.42 C, 1.50 Si, bal Fe, forged	78	0.0581	33
	273	(0.109)	
Manganese Steel			
38.9 Mn, 0.20 C, 0.70 Si, 0.055 S, 0.036 P, heated to 1000°C, quenched in water	15.35	0.0276	12
	18.40	0.0353	
	21.39	0.0425	
	76.6	0.107	
	93.1	0.119	
12.95 Mn, 0.09 C, 0.12 Si, 0.103 S, 0.050 P, heated to 1000°C, quenched in water	15.31	0.0211	12
	16.11	0.0225	
	17.48	0.0255	
	18.29	0.0271	
	19.91	0.0322	
	77.8	0.136	
	86.1	0.146	

TABLE III (Continued)

Thermal Conductivities of Ferrous Alloys

	T°K	k	Ref.
Manganese Steel (Continued)			
12.69 Mn, 1.27 C, 0.12 Si, heated to 1000°C, quenched in water	15.56	0.0128	12
	18.09	0.0148	
	21.06	0.0174	
	75.8	0.0660	
	88.2	0.0725	
2.23 Mn, 0.41 C, 0.07 Si, heated to 800°C, cooled in furnace	14.94	0.0330	12
	17.82	0.0417	
	21.33	0.0541	
	76.0	0.181	
	92.6	0.226	

TABLE IV

Miscellaneous Thermal Conductivities

			T°K	k	Ref.
Aluminum Alloys					
Aluminum-Antimony					
% Al	% Sb	ρ(23)			
100	0	33.8×10^{-4}	325	2.11	64
90	10	24.1	325	1.83	
80	20	17.9	325	1.59	
70	30	13.3	325	1.41	
60	40	7.90	325	1.00	
50	50	5.44	325	0.807	
40	60	1.79	325	0.477	
30	70	0.74	325	0.418	
20	80	0.014	325	0.218	
10	90	0.119	325	0.243	
0	100	2.05	325	0.201	
Aluminum-Chromium					
0.5 Cr, 0.28 Fe, 0.22 Si, bal Al			293	1.53	34
1.0 Cr, 0.28 Fe, 0.22 Si			293	1.13	34
2.0 Cr, 0.28 Fe, 0.22 Si			293	0.908	34
Aluminum-Copper					
% Al	% Cu	ρ(23)			
100	0	33.8×10^{-4}	326	2.11	64
90	10	26.0	326	1.61	
80	20	20.9	326	1.46	
70	30	18.5	326	1.30	
50	50	15.3	326	1.06	
40	60	10.6	326	0.753	
30	70	9.76	326	0.745	
20	80	3.60	326	0.293	
10	90	9.98	326	0.816	
0	100	50.8	326	3.85	

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

	T°K	k	Ref.
<u>Aluminum Alloys (Continued)</u>			
Aluminum-Copper (Continued)			
% Al % Cu			
50 50	325	1.18	29
40 60	325	0.753	
30 70	325	0.745	
20 80	325	0.293	
10 90	325	0.816	
10 90	293	0.510	
10 90	293	0.753	
0.50 Cu, 0.58 Fe, 0.91 Si, 0.50 Mg, wrought	298	1.87	54
Same, annealed	298	2.10	54
3.79 Cu, 0.96 Fe, 0.59 Mn, 0.49 Mg, 0.15 Si, bal Al, wrought	298	1.47j*	54

* Explanation of letters following the values of thermal conductivity (k) for Aluminum Alloys

a - cast specimen
b - cast, then annealed at ca 450°C
c - cast, annealed, then quenched from 500°C to 8°C in water and aged four to five hours
d - same as c, then aged two weeks
e - forged and cold drawn
f - same as e, then annealed at ca 500°C
g - annealed two hours at 700°F, cooled to 600°F at 25°F per hour, then furnace cooled
h - cast in green sand, quenched from high temperature solution treatment, aged at room temperature only
i - commercial forging stock reduced to one inch diameter by forging; quenched from high temperature solution treatment and subsequently given a low temperature precipitation treatment
j - same as i, but without the precipitation treatment
VZ - "Veredel." Zusatz

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

	T°K	k	Ref.
<u>Aluminum Alloys (Continued)</u>			
Aluminum-Copper (Continued)			
Same, annealed	298	1.79g	54
96.0 Al, 1.8 Cu, 0.9 Fe, 0.9 Cr, 0.4 Si, d = 2.74	303 303	1.05a 1.09b	4
4.39 Cu, 0.66 Si, 0.73 Fe, bal Al, sound casting	298	1.45h	54
Same, annealed	298	1.89g	54
5 Cu, 0.7 Si, 0.8 Fe, bal Al	293	1.33	34
5 Cu, 0.7 Si, 0.8 Fe, VZ = 0.1	293	1.88	34
5 Cu, 0.7 Si, 0.8 Fe, VZ = 0.25	293	1.40	34
5 Cu, 0.7 Si, 0.8 Fe, 0.02 Ti, VZ = 0.25	293	ca 1.7	34
5 Cu, 0.7 Si, 0.7 Fe, 0.5 Mn, VZ = 0.25	293	ca 0.7	34
5 Cu, 0.21 Si, 0.27 Fe, fused from 99.5 Al, 3 specimens of similar composition	293 293 293	1.52 1.56 1.60	34
5 Cu, 0.23 Si, 0.30 Fe, 0.03 Ti, VZ = 0.26	293	1.35	34
5 Cu, 0.21 Si, 0.27 Fe, VZ = 0.25 2 specimens of similar composition	293 293	1.32 1.26	34

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

	T°K	k	Ref.
Aluminum Alloys (Continued)			
Aluminum-Copper (Continued)			
5 Cu, 0.5 Mn, 0.27 Si, 0.31 Fe, VZ = 0.26	293	1.51	34
4.45 Cu, 0.50 Fe, 0.85 Si, 0.76 Mn, wrought	298	1.55	54
Same, annealed	298	1.97g	54
ca 95 Al, ca 0.5 Mg, ca 0.5 Mn, ca 4 Cu, ρ (23) = 19.10 x 10^{-4}	336	1.85	64
93.5 Al, 4.3 Cu, 0.9 Fe, 0.5 Mn, 0.4 Mg, 0.4 Si, d = 2.78	303	1.22a	4
	303	1.52b	
	303	1.48e	
	303	1.73f	
92 Al, 8 Cu, "American" alloy	303	1.30	4
90.9 Al, 8.1 Cu, 0.6 Fe, 0.4 Si, d = 2.80	303	1.39a	4
	303	1.67b	
	303	1.33c	
	303	1.32d	
89.9 Al, 8.4 Cu, 0.7 Mn, 0.7 Fe, 0.3 Si, d = 2.81	303	1.02a	4
	303	1.35b	
86.9 Al, 12.2 Cu, 0.6 Fe, 0.3 Si, d = 2.93	303	1.24a	4
	303	1.48b	

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

		T°K	k	Ref.
Aluminum Alloys (Continued)				
Aluminum-Iron				
Commercial:	% Al (bal Fe)			
	16.07	ca 313	0.100	55
	14.36	ca 313	0.167	
	12.39	ca 313	0.167	
	11.18	ca 313	0.209	
ca 0.8 Fe, 0.7 Si, 0.1 Cu + Zn, purified chill casting, fused from 98-99 Al, VZ = 1.0		293	1.35	34
0.8 Fe, 0.17 Si, VZ = 1.0		293	1.58	34
0.28 Fe, 0.22 Si, bal Al		293	2.10	34
Aluminum-Manganese				
0.5 Mn, 0.28 Si, 0.32 Fe, chill casting, not purified, fused from 99.5 Al		293	1.55	34
1.0 Mn, 0.35 Fe, 0.34 Si, bal Al		293	1.15	34
2.0 Mn, 0.43 Fe, 0.46 Si, bal Al		293	0.908	34
3 Mn, 0.49 Fe, 0.58 Si, VZ = 0.20,		293	0.816	34
2 specimens, similar composition		293	0.845	
97.52 Al, 1.07 Mn, 0.48 Cu, 0.66 Fe, 0.27 Si, $\rho(23) = 23.30 \times 10^{-4}$		336	1.69	64

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

			T°K	k	Ref.
Aluminum Alloys (Continued)					
Aluminum-Silicon					
5.04 Si, 0.95 Cu, 0.36 Fe, 0.34 Mg, sound casting			298	1.50	54
Same, annealed			298	1.90g	54
12 Si, 0.5 Mg, 0.5 Mn, technical alloy			293	1.27	34
14 Si, bal Al			303	1.6	4
87.3 Al, 11.9 Si, 0.8 Fe, d = 2.67			303	1.31a	4
			303	1.78b	
			303	1.73e	
			303	1.81f	
Skelron metal			303	1.03	4
Aluminum-Tin					
% Al	% Sn	ρ (22)			
100	0	33.8×10^{-4}	324	2.11	64
90	10	28.9	324	1.86	
70	30	22.8	324	1.73	
50	50	19.1	324	1.39	
40	60	17.8	324	1.25	
30	70	15.6	324	1.14	
20	80	13.1	324	0.950	
10	90	11.1	324	0.812	
0	100	8.96	324	0.627	

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

			T°K	k	Ref.
Aluminum Alloys (Continued)					
Aluminum-Tungsten					
1.0 W, 0.22 Si, 0.28 Fe			293	1.71	34
5.0 W, 0.21 Si, 0.27 Fe			293	1.55	34
Aluminum-Zinc					
% Al	% Zn	ρ(23)			
100	0	33.8×10^{-4}	323	2.11	64
90	10	25.0	323	1.62	
80	20	19.6	323	1.36	
70	30	18.7	323	1.33	
40	60	16.9	323	1.19	
0	100	17.0	323	1.16	
Aluminum-Copper-Iron					
9.6 Cu, 1.1 Fe			293	1.12	34
10.1 Cu, 1.5 Fe, 0.2 Si, 0.03 Mg			293	1.12	34
10.40 Cu, 1.40 Fe, 0.29 Mg, 0.59 Si, chill casting			298	1.43	54
Same, annealed			298	1.76g	54
Aluminum-Copper-Magnesium					
95.6 Al, 1.85 Cu, 1.5 Mg, 0.95 Fe, 0.1 Si, d = 2.62			303	1.57a	4
			303	1.65b	
			303	1.59c	

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

	T°K	k	Ref.
Aluminum Alloys (Continued)			
Aluminum-Copper-Magnesium (Continued)			
91.8 Al, 5.3 Cu, 1.15 Mg,	303	1.18a	4
0.8 Fe, 0.5 Mn, 0.45 Si	303	1.51b	
	303	1.23c	
	303	1.23d	
	303	1.36e	
	303	1.60f	
Aluminum-Copper-Manganese			
1 Cu, 3 Mn, 0.58 Si, 0.49 Fe,	293	1.10	34
VZ = 0.20, 2 specimens of	293	0.962	
similar composition			
3 Cu, 3 Mn, 0.58 Si, 0.49 Fe,	293	0.983	34
VZ = 0.20, 2 specimens of	293	0.740	
similar composition			
3 Cu, 3 Mn, 0.60 Si, 0.52 Fe,	293	0.669	34
0.03 Ti, VZ = 0.20, 2 specimens	293	0.766	
of similar composition			
6 Cu, 2 Mn, 0.44 Si, 0.41 Fe,	293	0.824	34
VZ = 0.20			
6 Cu, 2 Mn, 0.45 Si, 0.43 Fe,	293	0.761	34
0.02 Ti, VZ = 0.20			
86.0 Al, 12.2 Cu, 1.0 Mn, 0.6 Fe,	303	0.933a	4
0.2 Si, d = 2.92	303	1.33b	

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

	T°K	k	Ref.
Aluminum Alloys (Continued)			
Aluminum-Copper-Nickel			
93.6 Al, 2.5 Cu, 1.7 Ni, 0.9 Mg, 0.9 Fe, 0.4 Si	303	1.44a	4
	303	1.63b	
	303	1.38c	
	303	1.33d	
91.5 Al, 4.4 Cu, 2.05 Ni, 0.9 Mg, 0.65 Fe, 0.5 Si, d = 2.80	303	1.30a	4
	303	1.47b	
Aluminum-Copper-Silicon			
3.7 Cu, 4.7 Si, 0.5 Fe, 0.05 Mg, trace of Zn, Ni, bal Al	293	1.53	34
7.4 Cu, 2.0 Si, 0.5 Fe, trace Zn	293	1.35	34
87.0 Al, 6.1 Si, 3.8 Cu, 0.9 Fe, 0.6 Mn, d = 2.75	303	0.996a	4
	303	1.36b	
	303	1.16c	
	303	1.14d	
Aluminum-Copper-Tin			
90.9 Al, 6.9 Cu, 1.2 Sn, 0.7 Fe, 0.3 Si, d = 2.80	303	1.47a	4
	303	1.66b	
Aluminum-Copper-Zinc			
93.3 Al, 2.5 Cu, 2.6 Zn, 0.8 Fe, 0.5 Mn, 0.3 Si, d = 2.75	303	1.26a	4
	303	1.45b	
	303	1.32c	
88 Al, 2 Cu, 10 Zn, "German" alloy	303	1.5	4
2 Cu, 10 Zn, ca 0.7 Fe, ca 0.6 Si, VZ = 0.5	293	1.15	34

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

	T°K	k	Ref.
Aluminum Alloys (Continued)			
Aluminum-Copper-Zinc (Continued)			
84.3 Al, 2.7 Cu, 12.0 Zn, 0.6 Fe,	303	1.32a	4
0.4 Si, d = 2.94	303	1.33b	
76.2 Al, 2.6 Cu, 20.3 Zn, 0.55 Fe,	303	1.07a	4
0.35 Si, d = 3.20	303	1.08b	
	303	0.979c	
	303	0.975d	
Aluminum-Magnesium-Iron			
4.6 Mg, 2.1 Fe, 0.3 Cu, 0.3 Mn, 0.5 Si, 0.7 Zn, trace Ni	293	0.950	34
Aluminum-Manganese-Silicon			
10 Mn, 1.40 Si, 0.96 Fe	293	0.351	34
Aluminum-Silicon-Magnesium			
11.78 Si, 1.06 Mg, 0.84 Cu, 0.76 Fe, 0.96 Ni, wrought	298	1.67	54
Same, annealed	298	1.78g	54
Aluminum-Silicon-Nickel			
13.0 Si, 2.2 Ni, 0.9 Cu, 0.6 Mg, 0.03 Mn, trace Zn	293	1.19	34
Aluminum-Copper-Magnesium-Nickel			
94.8 Al, 1.8 Cu, 1.6 Mg, 1.0 Ni,	303	1.48a	4
0.5 Fe, 0.3 Si, d = 2.73	303	1.64b	
	303	1.45c	
Aluminum-Copper-Manganese-Silicon			
3 Cu, 3 Mn, ca 1.1 Si, ca 1.0 Fe,	293	0.887	34
VZ = 0.20, 2 specimens of similar composition	293	0.786	

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

	T°K	k	Ref.
<u>Aluminum Alloys (Continued)</u>			
Aluminum-Copper-Nickel-Magnesium			
3.94 Cu, 2.14 Ni, 1.52 Mg, 0.63 Fe, 0.55 Si, chill casting	298	1.44	54
Same, annealed	298	1.68g	54
3.84 Cu, 1.96 Ni, 1.29 Mg, 0.80 Fe, 0.55 Si, wrought	298	1.47i	54
Same, annealed	298	1.87g	54
Aluminum-Copper-Silicon-Iron			
5.1 Cu, 1.1 Si, 1.1 Fe, 0.1 Pb, 0.1 Zn	293	1.39	34
Aluminum-Copper-Silicon-Nickel			
2.1 Cu, 12.5 Si, 2.0 Ni, 0.6 Fe, 0.05 Pb, 0.8 Mg, 0.05 Mn	293	1.20	34
Aluminum-Copper-Tin-Nickel			
84.0 Al, 10.5 Cu, 3.3 Sn, 1.05 Ni,	303	1.35a	4
0.85 Fe, 0.3 Si, d = 2.93	303	1.59b	
Aluminum-Copper-Zinc-Iron			
7.06 Cu, 2.22 Zn, 1.21 Fe, 0.75 Si, sand cast	298	1.41	54
Same, annealed	298	1.70g	54
Aluminum-Copper-Silicon-Iron-Nickel			
4.5 Cu, 2.0 Si, 1.1 Fe, 4.4 Ni, 0.03 Mg, 0.02 Sn, trace Pb, Zn	293	1.13	34

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

				T°K	k	Ref.
Aluminum Alloys (Continued)						
Aluminum-Copper-Silicon-Iron-Zinc 6.2 Cu, 4.0 Si, 1.7 Fe, 1.5 Zn, 0.1 Mg, 0.03 Mn, 0.3 Ni, trace Pb, Sn				293	1.03	34
Aluminum-Copper-Silicon-Nickel-Zinc 4.1 Cu, 2.5 Si, 1.4 Ni, 1.0 Zn, 0.9 Fe, 0.7 Mg, trace Mn				293	1.19	34
Aluminum-Silicon-Nickel-Magnesium-Iron 13.80 Si, 2.45 Ni, 1.18 Mg, 1.09 Fe, 0.75 Cu, chill casting				298	1.14	54
Same, annealed				298	1.36g	54
Cadmium Alloys						
Cadmium-Bismuth						
	% Cd	% Bi	ρ(22)			
	100	0	13.76×10^{-4}	328	0.941	64
	90	10	8.92	328	0.720	
	80	20	6.47	328	0.598	
	70	30	5.24	328	0.489	
	60	40	3.86	328	0.393	
	50	50	3.51	328	0.339	
	40	60	2.35	328	0.251	
	30	70	2.13	328	0.209	
	20	80	1.75	328	0.163	
	10	90	1.36	328	0.130	
	0	100	0.84	328	0.079	

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

			T°K	k	Ref.
Cadmium Alloys (Continued)					
Cadmium-Thallium					
% Cd	% Tl	ρ(25)			
100	0	1.376×10^{-3}	336	0.941	64
90	10	1.22	336	0.866	
80	20	1.11	336	0.799	
70	30	1.02	336	0.753	
60	40	0.926	336	0.703	
50	50	0.877	336	0.661	
40	60	0.775	336	0.581	
30	70	0.690	336	0.535	
20	80	0.622	336	0.494	
10	90	0.570	336	0.443	
0	100	0.518	336	0.439	
Cadmium-Tin					
% Cd	% Sn	ρ(22)			
100	0	13.8×10^{-4}	326	0.941	64
90	10	12.7	326	0.874	
80	20	12.3	326	0.837	
70	30	11.4	326	0.782	
60	40	10.7	326	0.753	
50	50	9.98	326	0.699	
40	60	9.11	326	0.653	
30	70	9.17	326	0.644	
20	80	8.39	326	0.594	
10	90	7.73	326	0.556	
5	95	7.34	326	0.535	
0	100	8.96	326	0.627	

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

			T°K	k	Ref.
Cadmium Alloys (Continued)					
Cadmium-Zinc					
% Cd	% Zn	ρ (25)			
100	0	13.76×10^{-4}	326	0.941	64
90	10	13.91	326	0.954	
80	20	14.1	326	0.966	
70	30	14.4	326	0.996	
60	40	14.7	326	1.02	
40	60	15.5	326	1.04	
30	70	15.9	326	1.07	
20	80	16.3	326	1.09	
5	95	16.4	326	1.13	
0	100	17.0	326	1.16	
Copper Alloys					
Copper-Arsenic					
With a trace of As			293	1.42	29
With a large amount of As			293	0.416	
Copper-Manganese					
% Cu	% Mn	ρ (23)			
100	0	50.8×10^{-4}	332	3.82	64
90	10	2.76	332	0.272	
80	20	1.59	332	0.172	
70	30	1.11	332	0.134	
60	40	0.916	332	0.130	
40	60	0.820	332	0.113	
20	80	0.687	332	0.105	

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

			T°K	k	Ref.
Copper Alloys (Continued)					
Copper-Nickel					
% Cu	% Ni				
95.1	4.9		293	0.899	29
90.0	10.0		293	0.569	
79.9	20.1		293	0.330	
60.0	40.0		293	0.209	
39.1	60.9		293	0.230	
18.4	81.6		293	0.259	
0.0	100.0		293	0.590	
90.0	10.0		330	0.389	29
70.0	30.0		330	0.243	
60.0	40.0		330	0.226	
50.0	50.0		330	0.226	
40.0	60.0		330	0.226	
30.0	70.0		330	0.289	
20.0	80.0		330	0.305	
0.0	100.0		330	0.586	
94.1	3.9		293	0.870	29
88.7	17.3		293	0.339	
60.0	40.0		293	0.226	
55.0	45.0		293	0.230	
54.0	46.0		293	0.201	
28.0	70.0	2.0 Fe	293	0.347	
Constantan			293	0.280	

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

			T°K	k	Ref.
Copper Alloys (Continued)					
Nickel-Copper					
% Ni	% Cu	ρ (25)			
100	0	8.24×10^{-4}	330	0.586	64
80	20	3.00	330	0.305	
70	30	2.17	330	0.289	
60	40	2.02	330	0.226	
50	50	1.98	330	0.226	
40	60	2.04	330	0.226	
30	70	2.48	330	0.241	
10	90	3.49	330	0.389	
Copper-Phosphorus					
99.4 Cu, 0.63 P			303	1.05	2
98.4 Cu, 1.98 P			303	0.523	2
Copper-Silver					
% Cu	% Ag	ρ (25)			
100	0	5.45×10^{-5}	335	3.82	64
95	5	4.79	335	3.25	
90	10	4.20	335	3.02	
80	20	3.72	335	2.67	
70	30	3.59	335	2.63	
60	40	3.78	335	2.75	
55	45	4.46	335	3.14	
50	50	4.36	335	3.12	
47	53	4.48	335	3.11	
45	55	4.57	335	3.13	
40	60	4.50	335	3.11	
35	65	4.59	335	3.19	
25	75	4.74	335	3.30	
15	85	5.05	335	3.43	
5	95	5.13	335	3.52	
0	100	5.88	335	4.05	

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

			T°K	k	Ref.
Copper Alloys (Continued)					
Copper-Tin					
% Cu	% Sn				
95.0	5.0		293	0.736	29
90.1	9.9		286	0.439	
75.5	24.5		293	0.247	
24.9	75.1		293	0.581	
9.7	90.3		293	0.548	
0.0	100.0		293	0.594	
		% P			
91.7	8.0	0.30	293	0.452	29
87.2	12.4	0.40	293	0.364	
90.0	10.0	trace	293	0.418	
87.8	11.3	0.35	293	0.535	
Phosphor bronze; 0.02 or less Fe, 0.01 or less Pb, 0.01 or less Ni, 0.01 or less Zn					
% Cu	% Sn	% P			
96.84	3.11	0.02	293	1.17	28
96.50	3.09	0.39	293	0.67	
92.60	7.31	0.02	293	0.67	
92.20	7.41	0.38	293	0.46	
96.16	3.71	0.12	293	0.84	
94.60	5.27	0.09	293	0.75	
93.19	6.65	0.12	293	0.63	
Copper-Zinc					
89 Cu, 11 Zn			291	1.15	2
87 Cu, 13 Zn			291	1.26	
82 Cu, 18 Zn			291	1.31	
68 Cu, 32 Zn			291	1.09	
Red brass			273	1.03	2

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

	T°K	k	Ref.
Copper Alloys (Continued)			
Copper-Zinc (Continued)			
Yellow brass	273	0.854	2
Brass			
% Zn (bal Cu)			
3.11	293	2.73	29
5.00	293	2.14	
7.3	293	1.85	
11.0	293	1.14	
13.0	293	1.25	
14.3	293	1.37	
18.0	273	1.30	
18.0 small grain size	273	1.27	
18.0 large grain size	293	1.29	
27.9	293	1.17	
28.71 1% Sn + Pb + Fe	293	0.937	
30.0	293	1.09	
32.0	293	1.08	
33.1	293	1.11	
38.5 0.30 Mn	293	0.786	
89.15 Cu, 9.51 Zn, 0.02 Fe, 1.32 Pb, annealed 1/2-hr at 575°C, air cooled, accuracy 2%	293	1.81	29
81.18 Cu, 18.36 Zn, 0.02 Fe, 0.00 Pb, 0.20 Sn, annealed 2-hr at 700°C, air cooled, accuracy 2%	293	1.43	29
59.98 Cu, 37.88 Zn, 0.03 Fe, 2.01 Pb, 0.10 Sn, annealed 2-hr at 650°C, cooled 16-hr in furnace to 450°C, accuracy 2%	293	1.08	29

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

	T°K	k	Ref.
Copper Alloys (Continued)			
Copper-Zinc (Continued)			
71.09 Cu, 27.77 Zn, 0.02 Fe, 0.00 Pb, 1.02 Sn, annealed 3/4-hr at 700°C, air cooled, accuracy 2%	293	1.10	29
59.85 Cu, 39.36 Zn, 0.02 Fe, 0.07 Pb, 0.70 Sn, annealed 3-hr at 650°C, air cooled, accuracy 2%	293	1.17	29

The following 13 samples were air cooled, except for the last three, which were cooled in a furnace for 18 hours to 450°C

% Cu	% Zn	% Fe	% Pb	Annealing T°C	Annealing hr	grain dia, mm	Structure	k_{293}
99.64	0.35	0.02	0.01	650	1	0.070	α	3.70
99.45	0.51	0.01	0.01	650	1	0.110	α	3.63
98.93	0.95	0.02	0.00	700	1	0.120	α	3.31
96.94	3.04	0.02	0.00	700	3/4	0.100	α	2.68
95.21	4.77	0.02	0.00	700	3/4	0.085	α	2.42
90.07	9.91	0.01	0.01	700	3/4	0.095	α	1.87
83.20	16.76	0.03	0.01	700	3/4	0.125	α	1.51
79.62	20.35	0.01	0.02	700	3/4	0.190	α	1.40
69.14	30.81	0.03	0.02	650	3/4	0.075	α	1.21
65.43	34.53	0.01	0.03	650	3/4	0.080	α	1.20
59.20	40.75	0.02	0.03	650	3	0.070	α, β	1.27
54.96	45.02	0.02	0.00	650	2	0.40	α, β	1.49
50.30	49.45	0.01	0.04	650	2	16.0	α, β	1.78

	T°K	k	Ref.
Copper-Manganese-Nickel			
84 Cu, 12 Mn, 4.0 Ni	293	0.222	29
Copper-Nickel-Iron			
29.18 Cu, 67.10 Ni, 1.72 Fe, 0.16 C, 0.01 Si, 0.014 S, 0.024 P, 0.13 Mg, 0.04 Al, 0.33 Co, hot rolled, black surface	273	(0.21)	35

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

	T°K	k	Ref.
Copper Alloys (Continued)			
Copper-Zinc-Nickel			
63.0 Cu, 22.0 Zn, 15.0 Ni, 2	293	0.251	29
specimens of similar composition	293	0.247	
Copper-Zinc-Tin			
92.8 Cu, 2.0 Zn, 5.0 Sn, 0.15 P	293	0.791	29
88.0 Cu, 2.0 Zn, 10.0 Sn	293	0.494	29
87.8 Cu, 2.0 Zn, 10.0 Sn, 0.15 P	293	0.427	29
87.2 Cu, 2.2 Zn, 10.0 Sn, 0.35 Ni, 0.21 Fe	293	0.548	29
85.7 Cu, 7.2 Zn, 6.4 Sn, 0.6 Ni	293	0.598	29
85.0 Cu, 5.0 Zn, 8.7 Sn, 0.78 Pb, 0.21 Fe	293	0.703	29
Copper-Zinc-Manganese-Iron			
57.14 Cu, 37.5 Zn, 2.33 Mn, 1.8 Fe, 0.95 Al, 0.26 Sn	293	0.686	29
Iron Alloys			
Iron-Chromium			
85.15 Fe (diff), 13.65 Cr, 0.27 C, 0.29	273	0.245	35
Mn, 0.37 Ni, 0.37 Si, S, P (?)	373	0.25	
26.00 Cr, 0.13 C, 0.56 Mn, 0.10 Ni, 0.14 N, 0.12 P, 0.50 Si, 0.007 S, bal Fe, SS type 446	273	0.23	59

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

		T°K	k	Ref.
Iron Alloys (Continued)				
Iron-Cobalt	% Co			
Made from: iron with 0.09 C, 0.29 Cu, 0.31 Mn, 0.03 P, 0.11 Si, 0.03 S; cobalt with 0.24 C, 1.4 Fe, 1.1 Ni, 0.14 Si	0	303 (?)	0.456	2
	5	303	0.402	
	10	303	0.395	
	15	303	0.409	
	20	303	0.438	
	30	303	0.502	
	40	303	0.598	
	50	303	0.711	
	60	303	0.720	
	80	303	0.512	
	90	303	0.402	
	100	303	0.691	
Iron-Chromium	% Cr			
0.6 C max, cooled slowly from 900°C	0	303 (?)	0.418	2
	0.5	303	0.414	
	1	303	0.402	
	2	303	0.397	
	3	303	0.372	
	5	303	0.305	
	10	303	0.218	
	15	303	0.184	
	20	303	0.180	
Same, cooled rapidly from 1100°C	0	303 (?)	0.410	2
	0.5	303	0.372	
	1	303	0.368	
	2	303	0.364	
	3	303	0.238	
	5	303	0.184	
	8.5	303	0.163	
	13	303	0.138	
	17	303	0.130	

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

	T°K	k	Ref.
Iron Alloys (Continued)			
Iron-Manganese			
90 Fe, 10 Mn	-	0.130	2
11.57 Mn, 1.15 C, 0.055 P, 0.25 Si, 0.02 S, annealed at 810°C	298	0.192	8
Same, quenched from 902°C	298	0.138	8
Iron-Nickel			
3.45 Ni, 0.18 C, 0.67 Mn, 0.01 P, 0.16 Si, 0.02 S, annealed 700°C	298	0.37	8
Same, quenched from 902°C	298	0.35	8
4.48 Ni, 0.33 C, 0.405 Mn, 0.01 P, 0.16 Si, 0.03 S	298	0.36	8
Same, quenched from 830°C	298	0.32	8
94.36 Fe (diff), 3.55 Ni, 0.85 C, 0.39 C, 0.64 Mn, 0.21 Si, oil hardened, tempered 830/600°C	273 373	(0.335) 0.360	35
30.4 Ni, 0.26 C, 0.84 Mn, 0.14 Si, d = 8.125	302 344	0.12 0.13	2
Same, after cooling to 88°K	302	0.125	2

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

		T°K	k	Ref.
Iron Alloys (Continued)				
Iron-Nickel (Continued)	% Ni			
Made from: iron with 0.09 C,	0	303	0.410	2
0.29 Cu, 0.31 Mn, 0.03 P,	5	303	0.320	
0.11 Si, 0.03 S; nickel	10	303	0.258	
with 0.29 C, 0.24 Co, 4.20	15	303	0.218	
Cu, 1.25 Fe, 0.35 Mn, 0.15	20	303	0.175	
Si, 0.02 S; annealed at	23	303	0.171	
900°C, cooled to room temp.	25	303	0.130	
	30	303	0.0832	
	31.5	303	0.0782	
	33	303	0.0807	
	35.5	303	0.0807	
	40	303	0.0866	
	60	303	0.151	
	80	303	0.236	
	90	303	0.304	
	100	303	0.348	
Same, after suddenly cooling to	0	303	0.410	2
83°K and warming to room	5	303	0.302	
temperature	10	303	0.255	
	15	303	0.213	
	20	303	0.192	
	23	303	0.188	
	25	303	0.192	
	30	303	0.188	
	31.5	303	0.157	
	33	303	0.133	
	35.5	303	0.0807	
70 Fe, 30 Ni, "Climax"		ca 273	0.138	58

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

	T°K	k	Ref.
Iron Alloys (Continued)			
Iron-Silicon			
1.20 Si, 1.11 C, 0.40 Mn, 0.35 Cr, 0.06 Cu, 0.31 Ni, 0.04 S, 0.02 P, annealed at 950°C	298	0.259	8
Same, quenched from 830°C	298	0.188	8
3.65 Si, 0.10 C, 0.12 Mn, 0.03 P, 0.025 S, annealed at 985°C	298	0.230	8
Same, quenched from 907°C	298	0.205	8

Iron-Tungsten

These data are for specimens of various tungsten and carbon content, presumably at room temperature. The specimens in columns 2 and 3 were annealed at 900°C and cooled slowly to room temperature; those in column 4 were annealed at 1100°C, then quickly cooled. 8

Col 1 % W	Col 2 0.3 C	Col 3 0.6 C	Col 4 0.6 C
0	0.457	0.422	
0.5	0.419	0.374	
1	0.411	0.360	0.343
2	0.402	0.349	
3		0.356	0.280
5	0.390		
6	0.387	0.356	0.238
10		0.333	
15	0.324	0.309	
20	0.270	0.276	
25	0.220	0.231	

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

	T°K	k	Ref.
Iron Alloys (Continued)			
Iron-Chromium-Nickel			
73.49 Fe (diff), 17.87 Cr, 8.04 Ni, 0.15 C, 0.26 Mn, 0.19 Si, softened 1150/1200°C	273 373	(0.149) 0.16	35
18.42 Cr, 8.97 Ni, 0.17 C, 0.61 Mn, 0.51 Si, bal Fe, type 303 SS	273	0.142	59
18.00 Cr, 11.20 Ni, 0.069 C, 1.80 Mn, 0.70 Si, 0.021 P, 0.007 S, 0.77 Cb, SS type 347	273	0.19	59
50.98 Fe, 25.54 Cr, 20.68 Ni, 0.10 C, 1.83 Mn, 0.025 P, 0.84 Si, 0.005 S, SS type 310	273	0.13	59
4.12 Ni, 1.61 Cr, 0.14 C, 0.44 Mn, 0.01 P, 0.11 Si, annealed at 718°C	298	0.31	8
Same, quenched from 830°C	298	0.27	8
52.2 Fe (diff), 15.20 Cr, 26.86 Ni, 0.46 C, 1.18 Mn, 0.018 P, 1.30 Si, 0.014 S, 2.77 W, forged (Era-A. T. V.)	273 373	(0.11) 0.13	35
68 Fe, 29 Ni, 2 Cr, 1 Mn, "Climax 193"	ca 273	0.136	58
55 Fe (diff), 25 Cr, 20 Ni, austinetic, heat resisting	288	0.125	57

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

			T°K	k	Ref.
<u>Lead Alloys</u>					
Lead-Antimony					
% Pb	% Sb	ρ (25)			
100	0	4.76×10^{-4}	327	0.347	64
90	10	3.60	327	0.264	
80	20	3.10	327	0.230	
70	30	2.87	327	0.218	
60	40	2.66	327	0.213	
50	50	2.46	327	0.201	
40	60	2.33	327	0.201	
30	70	2.32	327	0.197	
20	80	2.29	327	0.188	
10	90	2.44	327	0.201	
0	100	2.47	327	0.201	
87 Pb, 13 Sb			313	0.26	4
Lead-Bismuth					
75 vol % Pb, 25 Bi			317	0.196	2
46 Pb, 54 Bi (eutectic)			313	0.0870	4
3.5 vol % Pb, 96.5 Bi			317	0.0540	2
Lead-Silver					
% Pb	% Ag	ρ (25)			
100	0	4.76×10^{-4}	325	0.347	64
90	10	4.57	325	0.351	
80	20	4.88	325	0.381	
70	30	4.95	325	0.395	
60	40	6.21	325	0.439	
50	50	6.15	325	0.489	
40	60	6.90	325	0.561	
30	70	7.14	325	0.577	
20	80	9.43	325	0.745	
10	90	12.17	325	0.987	
0	100	58.8	325	4.05	

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

			T°K	k	Ref.
Lead Alloys (Continued)					
Lead-Thallium					
% Pb	% Tl	ρ (25)			
100	0	4.76×10^{-4}	333	0.347	64
90	10	3.54	333	0.284	
80	20	2.98	333	0.251	
70	30	2.74	333	0.226	
60	40	2.62	333	0.201	
50	50	2.54	333	0.201	
40	60	2.63	333	0.226	
30	70	3.04	333	0.259	
20	80	4.02	333	0.322	
10	90	4.90	333	0.376	
6	94	5.16	333	0.402	
4	96	4.72	333	0.364	
2	98	4.95	333	0.385	
0	100	5.88	333	0.439	
Lead-Tin					
% Pb	% Sn	ρ (25)			
100	0	4.76×10^{-4}	327	0.347	64
90	10	4.95	327	0.360	
80	20	5.29	327	0.372	
70	30	5.65	327	0.385	
60	40	5.99	327	0.414	
50	50	6.47	327	0.464	
40	60	6.92	327	0.489	
20	80	7.62	327	0.544	
0	100	8.96	327	0.632	
62 Pb, 38 Sn (eutectic)			313	0.50	4
Lead-Bismuth-Tin					
33.3 Pb, 33.3 Bi, 33.3 Sn			285.7	0.127	2

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

		T°K	k	Ref.
Magnesium Alloys				
Magnesium-Aluminum				
95.82 Mg, 4.12 Al, 0.028 Fe, 0.019 Si, ρ (23) = 9.06×10^{-4}		336	0.665	64
89.82 Mg, 10.12 Al, 0.028 Fe, 0.023 Si, ρ (23) = 6.00×10^{-4}		336	0.485	64
Chill castings, with indicated % Al, bal Mg	% Al			
	2.1	300.0	0.887	8
	4.2	295.5	0.690	
	6.2	295.1	0.556	
	8.2	291.5	0.510	
	10.3	295.2	0.452	
	12.2	296.3	0.385	
Magnesium-Antimony				
Mg_3Sb_2, annealed at 500-600°C		Room (?)	0.0096	39
Magnesium-Nickel				
Annealed in vacuum, with:	1.9 Ni	293.4	1.36	8
	5.8 Ni	297.7	1.26	
Magnesium-Silver				
Annealed in vacuum, with:	2.2 Ag	298.7	1.31	8
	6.0 Ag	300.0	1.15	
Magnesium-Tin				
Annealed in vacuum, with:	2.2 Sn	294.0	1.06	8
	6.4 Sn	294.5	0.740	

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

					T°K	k	Ref.
Magnesium Alloys (Continued)							
Magnesium-Aluminum-Cadmium							
% Mg	% Al	% Cd	% Sn	& Zn			
93.0	4.0	1.0	1.0	1.0	295.2	0.556	8
92.5	4.0	2.0	1.0	0.5	295.3	0.632	
92.0	4.0	2.0	2.0		303.3	0.556	
92.0	4.0	3.0	1.0		295.3	0.694	
Magnesium-Aluminum-Zinc							
90.6 Mg, 6.0 Al, 3.0 Zn, 0.4 Cu, "Dow-metal"					302.6	0.611	8
Nickel Alloys							
Nickel-Chromium							
77.28 Ni (diff), 20.98 Cr, 0.59 Fe,					273	(0.125)	35
0.12 C, 0.65 Mn, 0.38 Si,					373	0.140	
Nichrome, forged and drawn							
Nickel-Manganese							
% Ni	% Mn	ρ (25)					
100	0	82.4×10^{-3}			333	0.586	64
90	10	27.7			333	0.310	
80	20	14.2			333	0.176	
70	30	10.4			333	0.155	
50	50	3.56			333	0.0920	
40	60	4.59			333	0.0962	
30	70	5.12			333	0.105	
10	90	5.58			333	0.0920	

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

			T°K	k	Ref.
Nickel Alloys (Continued)					
Nickel-Chromium-Iron					
73.19 Ni, 14.38 Cr, 6.99 Fe, 0.03 C, 0.03 Cu, 0.47 Mn, 0.39 Si, 0.007 S, 0.83 Al, Inconel X			273	0.134	59
% Ni	% Cr	ρ (25)			
100	0	82.4×10^{-3}	329	0.586	64
90	10	1.403	329	0.197	
70	30	0.845	329	0.109	
60	40	0.813	329	0.125	
50	50	0.830	329	0.117	
Tin Alloys					
Tin-Antimony					
% Sn	% Sb	ρ (25)			
100	0	8.96×10^{-4}	330	0.632	64
80	20	5.23	330	0.397	
70	30	4.59	330	0.351	
60	40	4.00	330	0.305	
50	50	3.46	330	0.268	
40	60	2.71	330	0.213	
30	70	2.29	330	0.197	
20	80	1.93	330	0.176	
10	90	1.90	330	0.188	
0	100		330	0.201	
Tin-Bismuth					
10 vol % Sn, 90 Bi			317	0.0527	2
75 vol % Sn, 25 Bi			317	0.326	2
25 Sn, 75 Bi			285.7	0.0962	2
50 Sn, 50 Bi			285.7	0.234	
75 Sn, 25 Bi			285.7	0.427	

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

			T°K	k	Ref.
Tin Alloys (Continued)					
Tin-Silver					
% Sn	% Ag	ρ (25)			
100	0	89.6×10^{-3}	333	0.632	64
90	10	87.0	333	0.602	
80	20	84.0	333	0.611	
70	30	82.6	333	0.611	
60	40	81.9	333	0.611	
50	50	80.7	333	0.577	
40	60	78.1	333	0.489	
27.5	72.5	52.4	333	0.393	
20	80	21.5	333	0.197	
10	90	30.2	333	0.297	
0	100	588.2	333	4.05	
Tin-Thallium					
% Sn	% Tl	ρ (25)			
100	0	8.96×10^{-4}	336	0.632	64
90	10	7.18	336	0.556	
80	20	6.26	336	0.485	
70	30	5.93	336	0.435	
60	40	5.48	336	0.418	
53.8	46.2		336	0.385	
50	50	4.77	336	0.372	
46.6	53.4	4.18	336	0.330	
40	60	3.47	336	0.289	
30	70	3.18	336	0.259	
20	80		336	0.255	
10	90	3.92	336	0.301	
0	100	5.88	336	0.439	

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

			T°K	k	Ref.
Tin Alloys (Continued)					
Tin-Zinc					
92 Sn, 8 Zn, eutectic			313	0.607	4
Tin-Bismuth-Lead					
33.3 Sn, 33.3 Bi, 33.3 Pb			285.7	0.127	2
Miscellaneous Alloys					
Boron Alloy					
ZrB_{12}			Room	0.122	56
Cobalt Alloys					
Cobalt-Chromium					
% Co	% Cr	ρ (27)			
100	0	6.86×10^{-4}	332	0.489	64
90	10	1.78	332	0.142	
70	30	1.26	332	0.130	
60	40	1.09	332	0.105	
Cobalt-Chromium-Tungsten					
More than 55 Co, less than 33 Cr, less than 6 W, Stellite No. 6			Room	0.148	53
Palladium Alloys					
Palladium-Gold					
90 Pd, 10 Au			298	0.519	2
50 Pd, 50 Au			298	0.360	
10 Pd, 90 Au			298	0.979	
Palladium-Platinum					
90 Pd, 10 Pt			298	0.561	2
50 Pd, 50 Pt			298	0.368	
10 Pd, 90 Pt			298	0.431	

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

			T°K	k	Ref.
Miscellaneous Alloys (Continued)					
Palladium Alloys (Continued)					
Palladium-Silver					
90 Pd, 10 Ag			298	0.477	2
50 Pd, 50 Ag			298	0.318	
10 Pd, 90 Ag			298	1.41	
Platinum Alloys					
Platinum-Gold					
90 Pt, 10 Au			298	0.761	2
60 Pt, 40 Au			298	0.259	
Single phase alloys:	% Pt	% Au			
	100	0	291	0.962	6
	96	4	291	0.460	
	90	10	291	0.351	
	75	25	291	0.238	
	55	45	291	0.209	
	45	55	291	0.209	
	32	68	291	0.230	
	16	84	291	0.481	
	8	92	291	0.799	
	0	100	291	3.09	
Platinum-Iridium					
80 Pt, 20 Ir			290	0.176	4
85 Pt, 15 Ir			290	0.234	
90 Pt, 10 Ir			290	0.310	
Platinum-Rhodium					
90 Pt, 10 Rh			290	0.301	4
Platinum-Silver					
30 Pt, 70 Ag			298	0.310	2
10 Pt, 90 Ag			298	0.979	

TABLE IV (Continued)

Miscellaneous Thermal Conductivities

	T° K	k	Ref.
Miscellaneous Alloys (Continued)			
Sodium Alloys			
Sodium-Potassium			
In ratio of atomic weights	313	0.607	4
In ratio of atomic weights	263.5	0.293	2
	279.2	0.230	
	294.8	0.244	
	316.1	0.259	

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INDEX FOR TABLES I, II, III, AND IV

Numbers refer to pages in the text. Alloying elements are listed in alphabetical order of their chemical symbols and in ascending order of number of alloying elements.

INDEX FOR TABLES I, II, III, AND IV (Continued)

INDEX FOR TABLES I, II, III, AND IV (Continued)

PART II

THE THERMAL CONDUCTIVITY OF A YELLOW BRASS AND OF CADMIUM

CHAPTER IV

MEASUREMENT OF THE THERMAL CONDUCTIVITY OF CADMIUM AND OF A FREE CUTTING YELLOW BRASS

Introduction.--It is the purpose of this chapter to describe the theory, the equipment and procedures used and the results obtained from the experimental work on brass and cadmium. The thermal conductivity of a given specimen can be calculated if the temperature gradient, heat input and dimensions of the specimen are known, as described in the next section. The experiments were designed so that these quantities could be readily measured, or else computed from readily measured quantities: the length and area from the physical dimensions of the specimen; the temperature difference from suitably arranged thermocouples; and the heat input from the voltage drop and current of an electric heater.

Briefly, the equipment consisted of a cryostat which had been designed and constructed for another purpose in the Low Temperature Laboratory of the Engineering Experiment Station at the Georgia Institute of Technology for use in a low temperature research program sponsored by the Office of Naval Research, Navy Department, under ONR contract number N6-ORI-192-NR-016-406, Project 116. Preliminary calculations indicated that it was not feasible to use this apparatus with materials of very low or very high thermal conductivity, so it was decided to use specimens of brass and cadmium for this work. Before measuring any thermal conductivities with the apparatus, it was necessary to make and calibrate two thermocouples for measuring the temperature gradient across the specimen and a copper resistance thermometer which was used in conjunction with a standard platinum resistance thermometer for calibrating the thermocouples. The experimental procedure was arranged so that all of these instruments could be calibrated in one run in which commercially pure copper was used as a heat conductor. The results of the experiment are described briefly in Chapter I and in detail in this chapter.

Theory of experiment. --The basic premises of the experiment can be explained by reference to Fig. 3. Heat is supplied to the specimen, S, by an electric heater, E, attached to the head, H. The heat passes through the specimen and enters the copper block, B. A grease joint, G, provides good thermal contact between the copper contactor, C, to which the specimen is soldered, and the

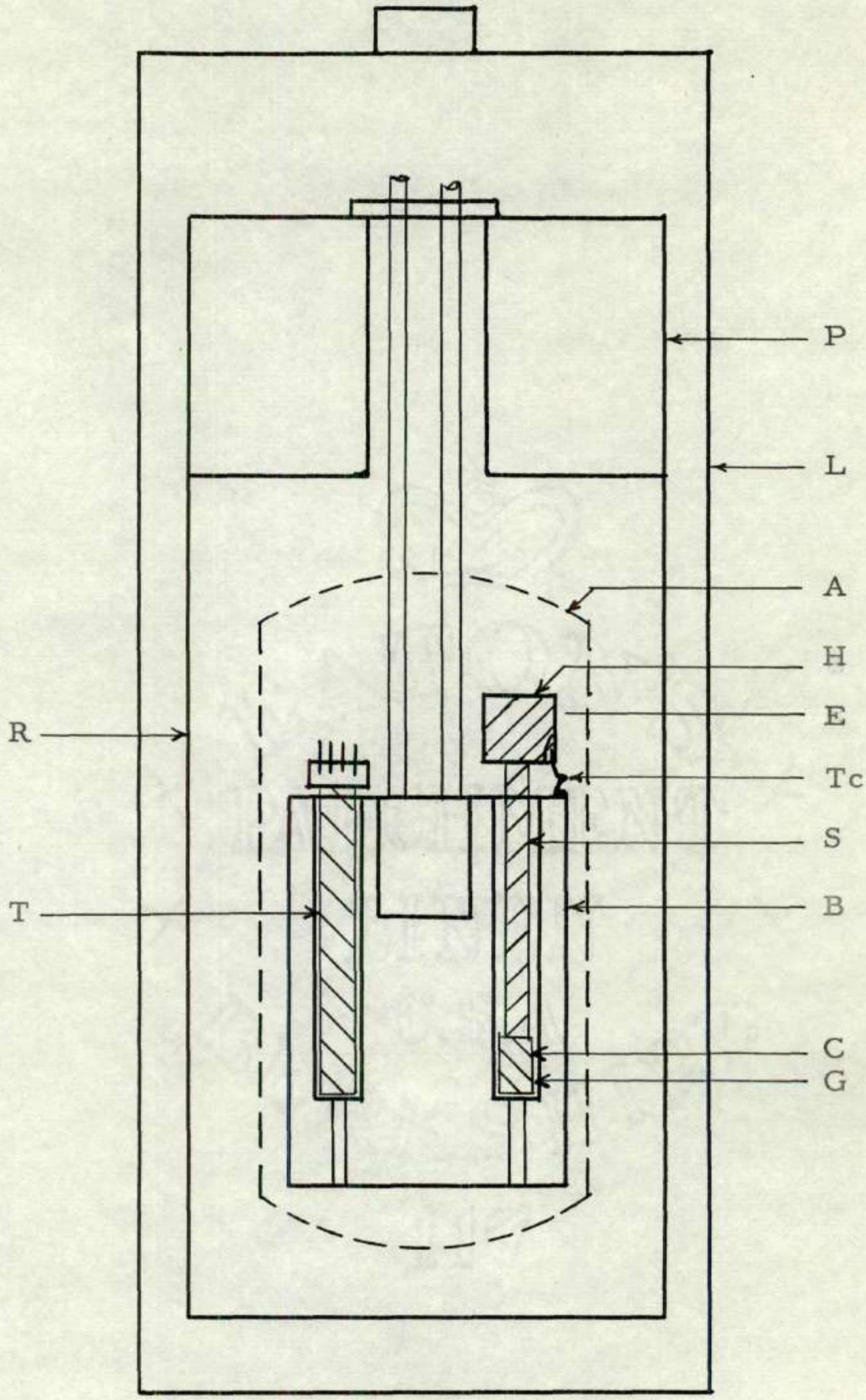


Figure 3

The Cryostat

copper block. The temperature of the copper block is measured by a standard platinum resistance thermometer, T. The temperature difference between the head and the copper block, $T_H - T_B$, is measured by a three-junction copper-constantan thermocouple, Tc. Radiation effects are minimized by the adiabatic shield, A, and a radiation shield, R. A refrigerant pot, P, aids in cooling the apparatus and absorbs heat conducted into it by electrical leads, refrigerant tubes and supports. The entire apparatus is enclosed in a vacuum case, L.

The idealized experiment can be considered the steady state case in which the copper block is so large that its temperature does not change with time. The temperature difference $T_H - T_B$ is then constant at equilibrium. In actual practice it is found that the temperature of the copper block rises slowly because of its finite heat capacity. It is further found that $T_H - T_B$ reaches a constant value while both the temperature of the head and the copper block rise slowly with time. Another complicating feature arises from the fact that the temperature T_B may be changing slowly due to heat flow along the supporting tubes. In practice this effect was found to be negligible, but a heater on the block would permit close thermostating, if necessary.

Consider now a specimen such as that in Fig. 4. The quantity of heat which will flow through the specimen under equilibrium conditions depends on the nature of the specimen material, its length and cross-sectional area, and the temperature gradient. It has been found that the quantity of heat required to maintain a given temperature gradient is directly proportional to the cross-sectional area and inversely proportional to its length:

$$Q = \frac{kA\,\Delta T}{L} \tag{12}$$

where k is the thermal conductivity of the specimen. Equation (12) applies only when the temperature gradient is constant with respect to time, the cross-sectional area and length are constant, and the heat flow is undirectional. The thermal conductivity varies only slightly with temperature and may be considered constant for small values of ΔT. The general equation of heat conduction, of which equation (12) is a special case, is derived in the Appendix.

The experiment described below was planned so that the necessary quantities, A, Q, ΔT, and L, could be measured and an equation with the form of equation (12) utilized in determining the thermal conductivity of cadmium and a free-cutting yellow brass over the temperature range 78° to 273° K.

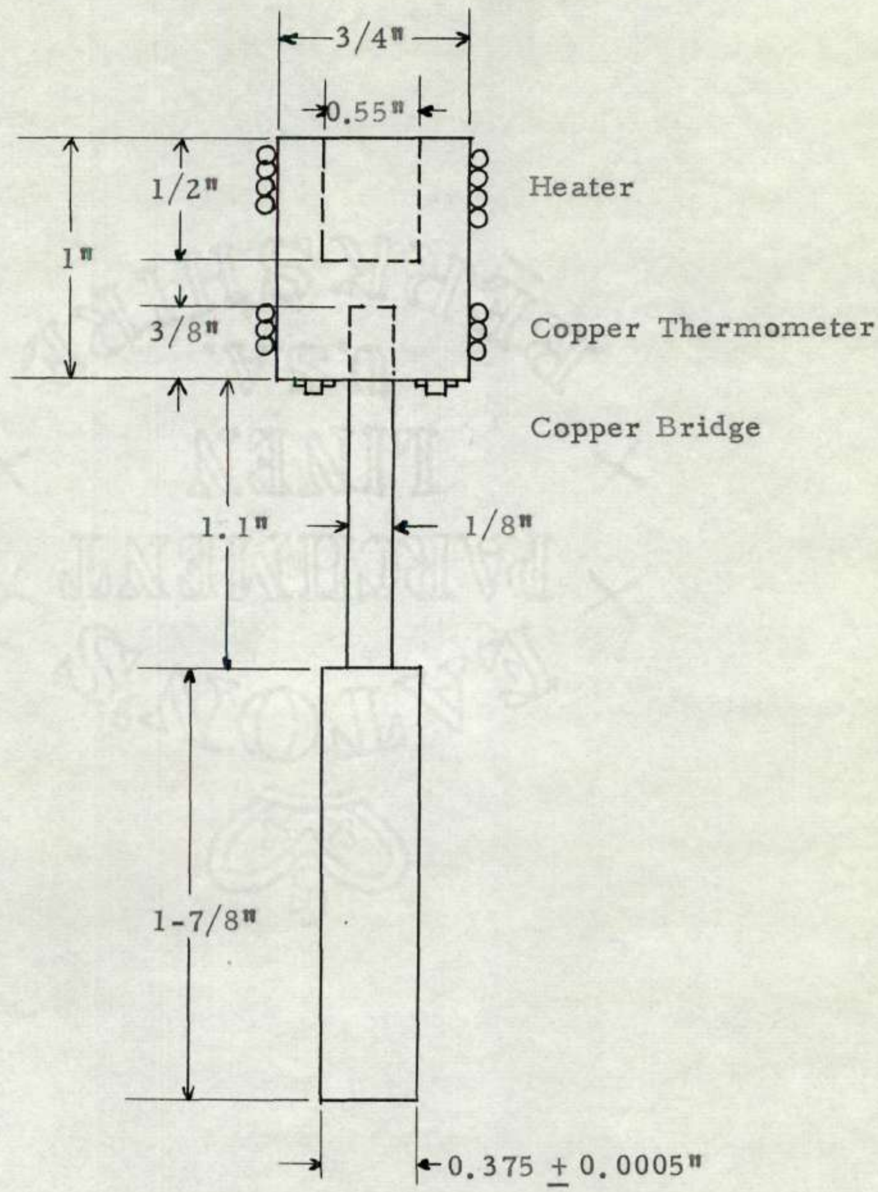


Figure 4

The Copper Specimen

The cryostat.--The cryostat is shown in Fig. 3. It consists of a heavy copper block, B, whose main function was to receive the heat input to the specimen at substantially constant temperature, the specimen, S, refrigerant pot, P, radiation shields, A and R, with attached apparatus. Refrigerant could be introduced into a cavity in the block through tubes with connections outside the cryostat. These tubes supported the block and the refrigerant pot, P, which in this work was used as an additional receptacle for refrigerant (liquid nitrogen) to aid in cooling the apparatus and for temperature control. Radiation shields, A and R, were provided to decrease the amount of radient heat transfer to the refrigerant. Thermocouples were attached between the top of the adiabatic shield, A, and the copper block, and between the top, middle and bottom of the lower part of the shield and the copper block. The potential developed by these thermocouples was indicated by a suitable potentiometer. Electrical resistance heaters attached to the shields were operated in series with variable resistances (to control the rate of energy input) to maintain the temperature of the shield, A, within 0.01°C of the block at all times. The vacuum case, L, was carefully soldered at the top to maintain a vacuum tight container. The necessary electrical leads, refrigerant tubes and supports entered the apparatus through permanently sealed openings in the cover plate. The entire apparatus was surrounded by a large Dewar flask (not shown) which contained the liquid nitrogen or dry ice-alcohol baths.

Vacuum was maintained inside the cryostat by an oil diffusion vacuum pump. The suction of the pump was attached to the apparatus through a system of glass work which contained a McCleod gauge for measuring the absolute pressure of the system and a container for a heat exchange gas (helium) which could be admitted to the cryostat when a more rapid heat transfer between the refrigerant bath and the cryostat was desirable. The diffusion pump and the cryostat were protected from mercury vapor by liquid nitrogen "cold traps" located on either side of the manometer. Thermal conductivity measurements were made at a pressure of 10^{-5} mm Hg or less to eliminate or minimize heat losses by conduction through the atmosphere surrounding the specimen.

Sufficient electrical leads (B. & S. No. 34 single cotton enameled wires) were provided to measure thermocouple potentials, platinum and copper thermometer resistances, and heater currents and voltages, as will be described. All leads from the copper block were wrapped around the block and in good thermal contact with it. They went next to the refrigerant pot, P, with which they were also in good thermal contact. The refrigerant pot absorbed heat which was conducted inside the apparatus by electrical leads or supports. The leads were carried from the refrigerant pot to the appropriate instrument outside the cryostat.

The specimens.--Three specimens were used. One of commercial copper was used in the calibration of the copper thermometer and the two thermocouples. It consisted of a rod turned to the dimensions indicated in Fig. 4; note that part of the specimen was turned to 1/8-inch diameter and part to 0.375 inch. A specimen of a free cutting yellow brass, obtained from the commercial stock of the J. M. Tull Metal and Supply Company of Atlanta, Georgia, consisted of a 3/16-inch diameter rod which was turned down from a 3/8-inch rod. Pertinent dimensions and assembly details are shown in Fig. 5. The nominal composition of the brass was 62.0 per cent copper, 35.0 per cent zinc and 3.0 per cent lead. A cadmium sample in the form of a cast stick was obtained from A. D. Mackay, New York, New York, and stated to be 99.95 per cent pure. The casting was turned to the same dimensions as the brass.

The assembly of the specimens is shown in Figs. 4 and 5. The assembly of the cadmium and brass specimens was identical but differ from that of the copper specimen. The specimens were soldered to their respective heads and copper contactors, in the case of brass and cadmium, with Wood's metal to insure a strong joint with good thermal contact. The copper contactors were covered with a layer of Vaseline (white petroleum jelly) and then placed in a hole in the copper block (radial clearance, 0.001 inch).

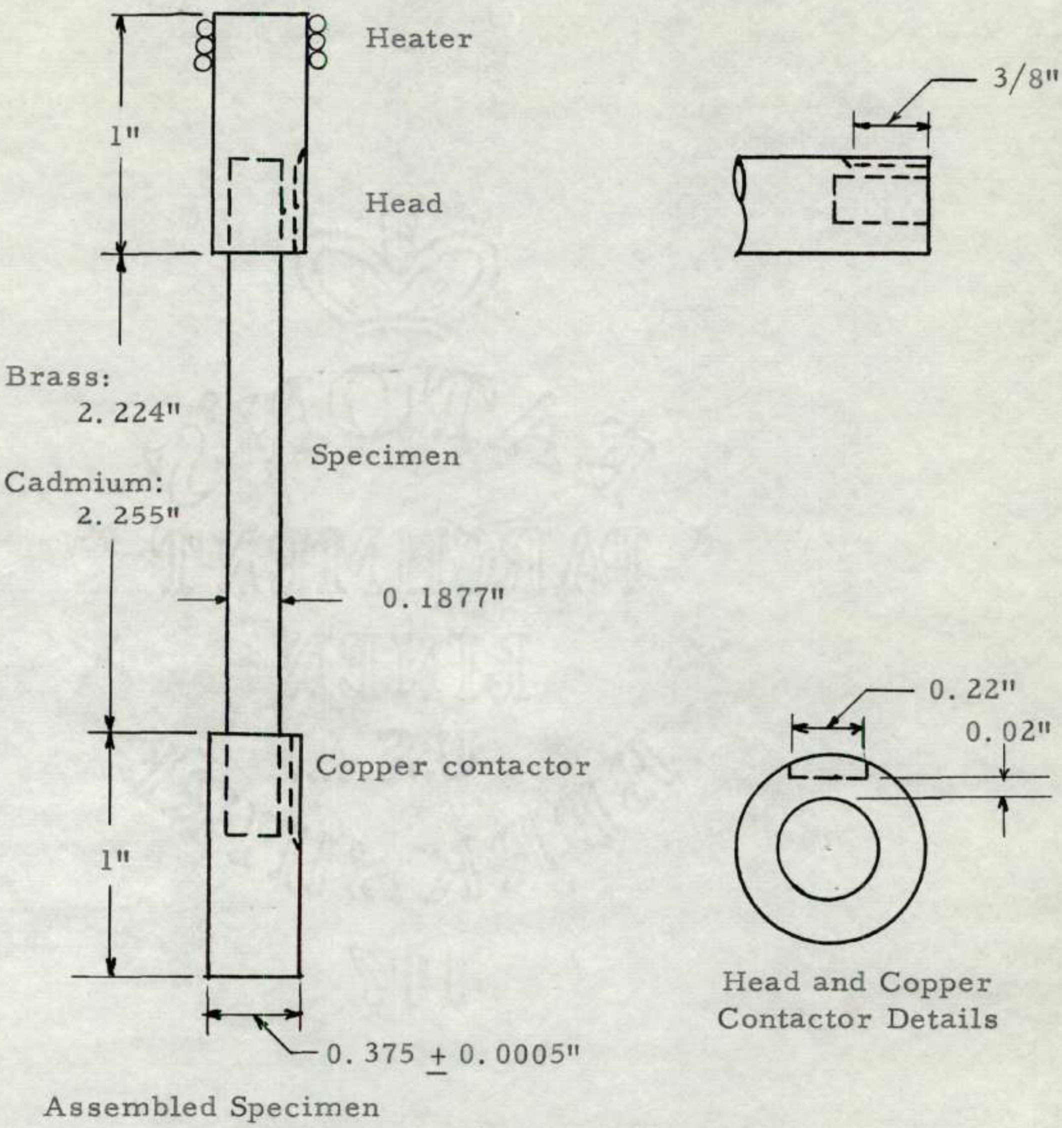


Figure 5

Brass and Cadmium Specimen Assembly

The Vaseline was used to provide good thermal contact between the specimen and the copper block when the cryostat was evacuated. The problem of thermal contact was one which required attention whenever two surfaces were in contact under vacuum.

The design of the heads used on the specimens required special attention. It was anticipated that the use of three junction copper-constantan thermocouples would give the temperature difference across the specimen accurate to 0.01°C. Now, if the head were large, the amount of heat required to raise its temperature at the rate of, say 0.005°C per minute, would be large compared to the heat required to maintain a temperature gradient of 2.0°C and the accuracy of the experiment would be seriously impaired. This would be especially important if the specimen had a low thermal conductivity, which is the reason it was considered not feasible to use such a specimen. For this reason it was imperative to make the heads as light in weight as possible. The head used in the calibration experiment had to carry a heater, the copper thermometer and two thermocouples, so a certain minimum size was necessary; the weight of the head was reduced by drilling a large hole in it, as indicated in Fig. 4.

The diameter of the brass and cadmium specimens was increased to 3/16-inch so that more heat would be required to maintain the desired temperature gradient and a smaller fraction of the total heat input would go into raising the temperature of the head; a greater temperature gradient would have the same effect. A temperature difference of 2.0°C had been planned, but the difference actually used was closer to 2.5°C. Smaller heads were possible with these specimens since only one thermocouple and a heater were attached to each. Both a head and a copper contactor were needed for these specimens. These identical pieces were of copper and were attached with Wood's metal. A slot was machined in the copper contactors and heads to permit soldering a thermocouple junction in such a way that there would be no contact between the copper block and the thermocouple when the specimen was in place (see Fig. 5).

The copper thermometer and heaters were attached to the heads after they were attached to the specimens. The thermometer consisted of about six feet of No. 40 gauge copper wire to each end of which was attached a short length of No. 36 gauge copper wire, which was somewhat stiffer and better suited for making junctions. Two leads were required at each end of the thermometer, one to carry the heating current and one connected to the Mueller Temperature Bridge. The No. 40 copper wire was taken from a spool labeled "Elect. Resist. set-up and Blomeke's High Temp. Cal. WTZ". The resistance after assembly was approximately 8.5 ohms. The specimen heaters consisted of about 3.5 feet of No. 40 gauge constantan wire which was wrapped as closely as possible to the top of the head. The final resistance of the heaters was 100 to 110 ohms. Again, two leads at each end of the heaters were necessary, one to carry the heating current from a wet cell battery and one for measuring the voltage drop across the heater.

Essentially the same procedure was used for winding the heaters and the copper thermometer. One end was securely tied in place with ordinary No. 60 sewing thread. A coat of GE adhesive diluted to about half strength with GE thinner was applied to the head. The adhesive helped to hold the wire in place as it was wound and provided intimate thermal contact between the heaters or thermometer and the head when the cryostat was evacuated. The wire was held under very slight tension while it was being wound and was kept in close contact with previously wound wire so that as little distance as possible along the head would be needed, but no wires were allowed to cross each other. The second end was tied down in the same manner as the first. Two more coats of thinned GE adhesive and a coat of full strength adhesive were added to insure good thermal contact.

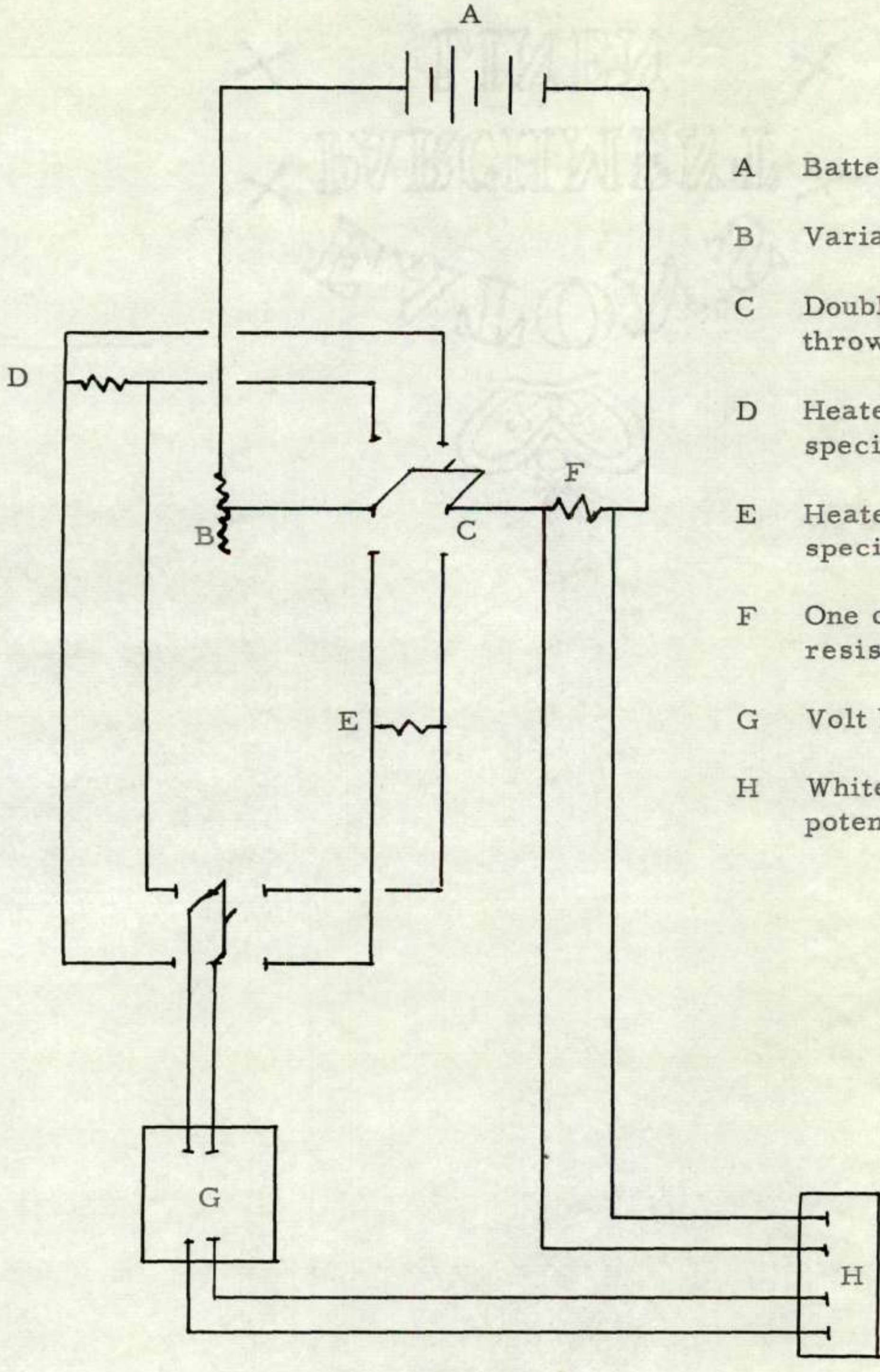
The potential and current connections were made by cleaning about one half inch of insulation off the ends of the wires to be joined. The ends were then wrapped around each other and good electrical contact insured by a small drop of solder. The junction was then insulated with full strength GE adhesive and covered with scotch tape.

The thermocouples. --Two three-junction copper-constantan thermocouples were made and calibrated; after these were calibrated it was decided that two more would be needed for the brass and cadmium experiments. The second two were made from the same wire and the calibration was taken to be the average of the first two. The copper wire was taken from a roll of No. 38 gauge wire labeled "Cu wire for Tc. WHW" and dated 7-6-54. The constantan wire was taken from a roll labeled "Resist. Thermom. I; Helium Cryostat" and dated 8-7-47. The thermocouples were made from three lengths of constantan wire and two lengths of copper wire, each approximately twenty centimeters long, with two longer lengths of copper wire for making necessary electrical connections. About one half inch of insulation was cleaned from the end of each wire and then a copper and a constantan wire were wrapped together and soldered. The junction thus made was insulated with a drop of GE adhesive and covered with scotch tape. When all six junctions were made the total resistance was measured and recorded. The ends of the thermocouple were then mounted in a receptacle made from thin copper plate. A strip of copper plate about 3/8-inch wide by 3/8-inch long by 0.010 inch thick was bent into a "U" shape. A piece of scotch tape was attached to the inside of the "U", a drop of GE adhesive added, a strip of mica and another drop of adhesive added, all on the inside of the "U". The individual junctions were then placed in the "U", with a drop of adhesive between each junction. A second piece of mica was placed on top of the junctions, a drop of adhesive added and the ends of the "U" bent down to form a firm junction. The total resistance of the thermocouple was again measured and compared with the previous resistance to check the electrical insulation. The assembled junction was 0.055 inch thick.

Small bridges made from thin copper plate were soldered to the under side of the head of the copper specimen, as shown in Fig. 4. Similar bridges were soldered to the copper block. These bridges made a tight receptacle for the ends of the thermocouples. The junctions and bridges were covered with Vaseline to aid in securing good thermal contact. Slots were machined in the heads and copper contactors of the brass and cadmium specimens and the copper sheathed thermocouple junctions were soldered in place. In the calibration experiment, thermocouples were attached to the head and the copper block; in the thermal conductivity measurements, thermocouples were attached to the head and the copper block and to the copper contactor and the copper block. This latter arrangement permitted a direct measurement of the temperature gradient across the grease film.

The copper block.--The copper block consisted of a cylinder of commercial copper 2-1/16-inches in diameter by three inches long, and which weighed approximately 1100 grams. The block had four holes, 0.377 ± 0.0005 inch in diameter by 2-3/4-inches deep, drilled and reamed in it. Fig. 3 shows the copper block with a specimen in place. The copper block had several useful functions, the principal one of which was to receive heat at substantially constant temperature. It also supported the specimen and the standard platinum resistance thermometer.

Electrical circuits.--The electrical circuits for the heaters are shown in Fig. 6. A wet cell battery, A, was used as a source of electrical energy. A variable resistance, B, was used to control the energy input to the heater. A double pole-double throw switch, C, was used to select the desired heater; this switch was not required in the calibration experiment as only one heater was used. Leads for



A Battery

B Variable resistance

C Double pole double throw switch

D Heater for copper specimen

E Heater for cadmium specimen

F One ohm standard resistance

G Volt box

H White double potentiometer

Figure 6

Electrical Circuits for Heaters

each heater led from a junction at each end of the heater through a double pole-double throw switch into a volt box which reduced the voltage to a vlue which could be safely measured by the potentiometer. The voltage drop across a standard one ohm resistance in the main circuit was measured directly by the potentiometer.

The potentiometer used was a White Double Potentiometer manufactured by the Leeds and Northrup Company and assigned L. and N. No. 713542. The one ohm resistance was L. and N. No. 649470 and in 1947 was certified to have had a resistance of 1.00000 international ohms at 25°C when used as a four terminal resistor; it therefore measured the current directly. The 150,000 ohm volt box (Ser. No. 688172) was also made by Leeds and Northrup.

The thermocouples were connected directly to the White Potentiometer by appropriate leads from the cryostat; the potential developed was read directly. The resistance thermometers were connected directly to the Mueller Temperature Bridge (L. and N. No. 740545).

<u>The thermocouple calibration experiment.</u>--This calibration experiment was designed to calibrate two thermocouples, which were required for the subsequent experiments, simultaneously with the copper resistance thermometer. After placing the copper specimen

in place in the copper block, the two thermocouples were attached to the head of the copper specimen by means of the bridges on the head (see Fig. 4), and to the copper block by similar bridges on it. The heater, the copper resistance thermometer, the two thermocouples and the standard platinum resistance thermometer were connected to their respective electrical circuits. The assembly of the cryostat was then completed and the apparatus evacuated to 10^{-5} mm Hg or less, as indicated by the McCleod gauge. Before introducing the liquid nitrogen into the Dewar flask, some preliminary experimentation was done so that some experience in operating the equipment could be obtained and the operating characteristics of the apparatus learned. The operation of the instruments required two people, one to operate the shield controls to keep the temperature of the adiabatic shield and the copper block the same, and one to measure and record the heater voltage and amperage, the thermocouple potentials, and the resistance of both thermometers.

The method of calibration was to bring the copper block and the specimen head to the same temperature, as indicated by a constant, near zero, reading of the thermocouple potential. When the constant reading was obtained the resistance of the two thermometers was measured on the Mueller Temperature Bridge. The standard thermometer, designated Th-2, had been previously calibrated (Project 116) against a thermometer (L. and N. No. 1048215) which, in turn, had been calibrated by the Bureau of Standards. When two or three readings had been obtained for each thermometer the heater on the head was turned on with sufficient resistance in the circuit to give a temperature difference of 2° - 3° C across the specimen. This phase is called a "thermal conductivity" experiment. The thermocouple potentials were followed until the system was at equilibrium, i. e., until the thermocouple potentials were constant with respect to time. This required fifteen to twenty minutes. The resistance of both thermometers and both thermocouple potentials was then measured as a function of time. After each measurement had been made at least twice the head heater was turned off and the heater on the copper block turned on. The block and specimen were heated until they were at the temperature of the head during the "thermal conductivity" experiment, this temperature being indicated by the resistance of the copper thermometer. A short time was allowed for the system to come to thermal equilibrium and the resistance of the two thermometers was again measured. The copper block and specimen were then heated to the temperature of the next series of measurements and the entire sequence repeated until the temperature range from 78° to 273° K was covered.

Since the resistance of the standard thermometer as a function of temperature was known, the calibration of the copper thermometer was accomplished when the temperature corresponding to a measured resistance of the standard thermometer was calculated. When the calibration of the copper thermometer was finished, the temperature drop across the specimen (with the head heater on) could be computed and the calibration of the thermocouples completed.

Calibration calculations.--The calculations involved were, first, the conversion of the measured resistances of the two thermometers to the same instant of time and the determination of the temperature corresponding to the resistance of the standard thermometer during the equilibrium measurements before and after the "thermal conductivity" measurement made at each calibration point. Next, the temperature difference between the copper block and the head was determined for this "thermal conductivity" experiment from the measured resistances of the two thermometers. The calibration of the two thermocouples was then possible. Sample calculations for all of the operations are included in the Appendix.

The Mueller Temperature Bridge used in these experiments to measure thermometer resistances was designed to eliminate the resistance of leads to and from the particular resistance whose value is desired. The average of two resistances, one measured in each direction in which a battery potential can be impressed, is required. The instrument was provided with a circuit selector switch with "N" and "R" positions for reversing the potential direction. In these experiments readings were taken with the instrument on one position at 15 to 20 second intervals to permit determination of the direction and rate at which the resistance was drifting and, once for each calibration point, the galvanometer sensitivity. The circuit selector switch was then moved to the other position and the procedure repeated. This procedure gave two sets of readings with a 60 to 100 second interval between them, but a measurement for each circuit at the same instant was necessary for averaging the two resistances. This presents no great problem, however. Since the drift rates are known, a reference time can be chosen and the resistance as measured on one or both circuits can be calculated for this time by a simple linear extrapolation. Corrections for instrument zero and dial settings were applied to the average resistance to give the true resistance at each point.

The purpose of this part of the experiment was to calibrate the copper thermometer. This required a knowledge of the resistance of both thermometers at the same instant. Since only one temperature bridge was available it was necessary to measure the resistance of the two thermometers alternately. The instantaneous resistances, calculated as described above, were finally plotted as a function of time. Straight line plots were the usual result and linear interpolations or extrapolations could be used to find the resistances of the two thermometers at the reference time chosen. The two resistances so obtained correspond to the same temperature. This temperature can be found from the known temperature-resistance relation of the platinum thermometer. The temperature-resistance relationship of the copper thermometer was thus determined over the desired temperature range.

The conversion of the platinum thermometer resistance to temperature was done by the method of Werner and Frazer (85) for temperatures above 83°K and by the method of Los and Morrison (86) for temperatures below 83°K. The method of Werner and Frazer required appropriate substitution in equation (13) and linear interpolation in their tables to find the temperature corresponding to R'. In this equation R is the resistance of the standard platinum thermometer

$$R' = a R + b \tag{13}$$

(Th-2), R' is the ratio of the resistance at T°K to that at 273°K and a and b are constants. Calculation of the two temperatures below 83°K was done by Experiment Station personnel.

The calibration of the thermocouples could be made once the temperature-resistance relationship of the copper thermometer was established. In this part of the experiment the head heater was on and a constant temperature differential of about 2.5°C was maintained between the head and the copper block. The thermocouple potential was constant, but the temperature of the head and the copper block was drifting slowly upward. It was consequently necessary to use the procedure outlined above to find the resistance of the two thermometers at the same instant so an accurate temperature difference could be determined. The thermocouple potential was read directly from the White Potentiometer, it being necessary only to measure the sensitivity of the galvanometer so corrections could be made for non-zero readings. The thermocouple potential was divided by the measured temperature difference to complete the calibrations. The calibration of the copper thermometer and the two thermocouples is given in Tables 6 and 7 (Appendix) and Figs. 7 and 8, respectively.

Experimental procedure for brass and cadmium. --The assembly of the apparatus for these specimens was very similar to that for the calibration experiment. The two specimens were placed in the copper block with two thermocouples on each specimen. The results of the calibration experiment indicated that the temperature drop across the Vaseline film might be appreciable, so two new three-junction thermocouples were made from the same spools of copper and constantan wire used to make the calibrated couples. One of the calibrated couples was used on each specimen to measure the temperature difference between the head and the copper block and one of the new couples was used to

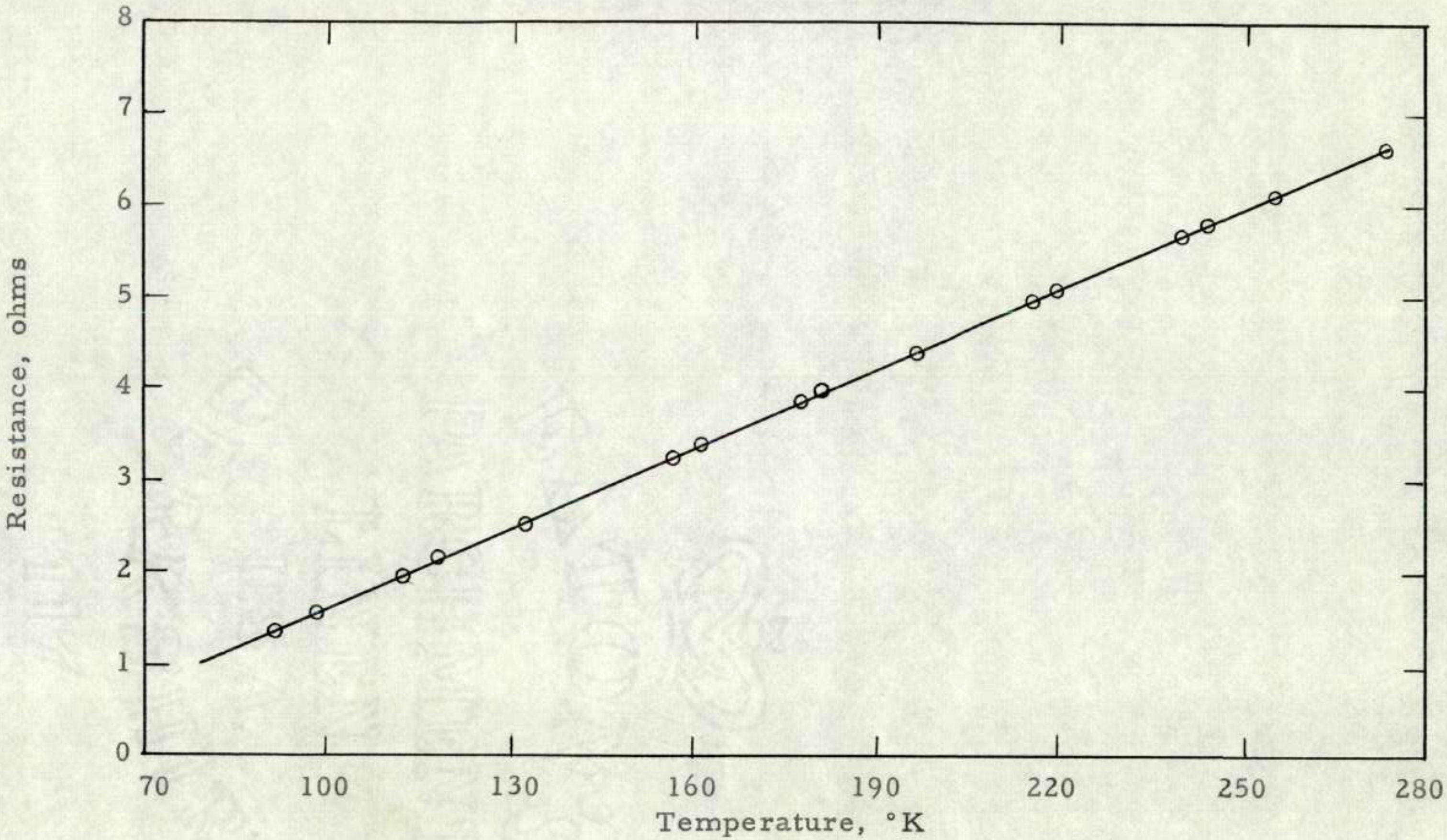


Figure 7

Resistance of Copper Thermometer vs Temperature

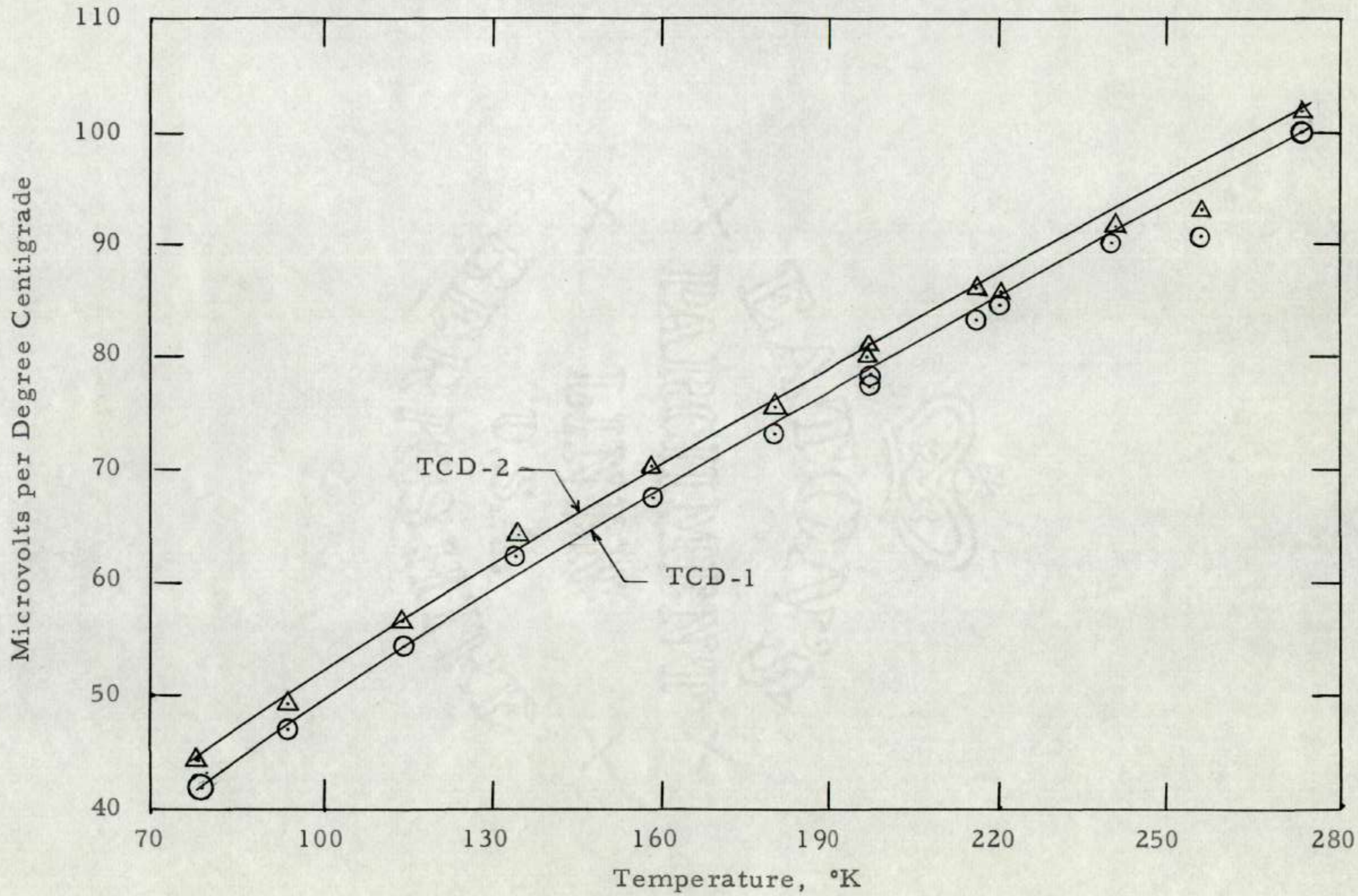


Figure 8

Calibration of Three-Junction Copper-Constantan Thermocouples measure the temperature difference between the copper contactor and the block. The new thermocouples were similar to the calibrated ones. A rough check on their calibration was made by immersing one end of both new couples and one end of a calibrated couple in an ice-water bath and the other ends in a water bath at room temperature. Both baths were in Dewar flasks to minimize temperature fluctuations. The voltage developed by the new couples under these conditions agreed closely with that of the calibrated couples, so the calibration assumed for the new couples was the average of the calibrated couples. This was justified on the basis that the temperature drop across the vaseline film was a relatively small percentage of the total temperature drop, so a large error in its measurement would cause only a small error in the final results. Other differences were that only the standard thermometer (Th-2) was used and the use of the double throw switches to select the brass or cadmium specimen.

The experimental procedure was altered only in that two sets of measurements were made at each temperature and only one resistance thermometer was used. The experiment ran much more smoothly than the calibration run for two reasons: first, the thermal conductivity of the brass and cadmium was only about one fourth that of copper and less heat input was necessary to maintain the desired temperature difference, and consequently conditions in general, and especially the temperature of the copper block, were more stable; second, the experience gained in the calibration run made the experimental runs easier.

Thermal Conductivity Calculations. --It was necessary to calculate temperatures from the resistance of the standard thermometer, the energy input to the heaters and the temperature drop across the specimen. The conversion of resistance to temperature is described above. The energy input is calculated from the voltage drop across the heater and across a one ohm standard resistance. The voltage drop across the one ohm standard resistance is numerically equal to the amperage. The voltage drop across the heater was measured by the White potentiometer after being reduced to 0.01 of its value in the volt box. The potential developed by the thermocouples is a measure of the temperature difference between the head and the copper block. Corrections due to heat flow in the heads and temperature rise of the specimens and heads during the experiment are necessary. Radiation is neglected. With this information the thermal conductivity of the specimens can be calculated from equation (21). Sample calculations are given in the Appendix.

The Thermal Conductivity of Brass. --The thermal conductivity of brass was found to vary almost linearly from 0.434 watts/cm°C at

80°K to 1.18 watts/cm°C at 275°K with an estimated maximum error of ten per cent. Corrections arise from the method of attaching the thermocouples, the thermocouples not reading zero with no temperature difference in the calibration experiment, heat flow pattern in the head, temperature rise of head and specimen during experiment, radiation and conduction of heat from the head to the copper block by electrical leads and thermocouple wires. Errors due to these corrections vary from negligible for radiation to an estimated five per cent for failure of the thermocouples to read zero. These corrections are discussed in detail below where the accuracy of the experiment is considered and in the sample calculations in the Appendix.

The results for brass compare very favorably with theory and values reported by other investigators. According to the theory discussed in Chapter II, the thermal conductivity of an alloy should decrease with temperature and this is indeed the case. The slope is steeper than Lees (26) reports for a 70 Cu - 30 Zn yellow brass and slightly steeper than Aoyama and Ito (32) report for a 64 Cu - 36 Zn brass, although they report values for 78° and 273°K only. The presence in our sample of lead, about three per cent by weight, will not affect the conductivity greatly as it is insoluble in the copper-zinc alloy. The final results are shown in Fig. 9 and Table 2.

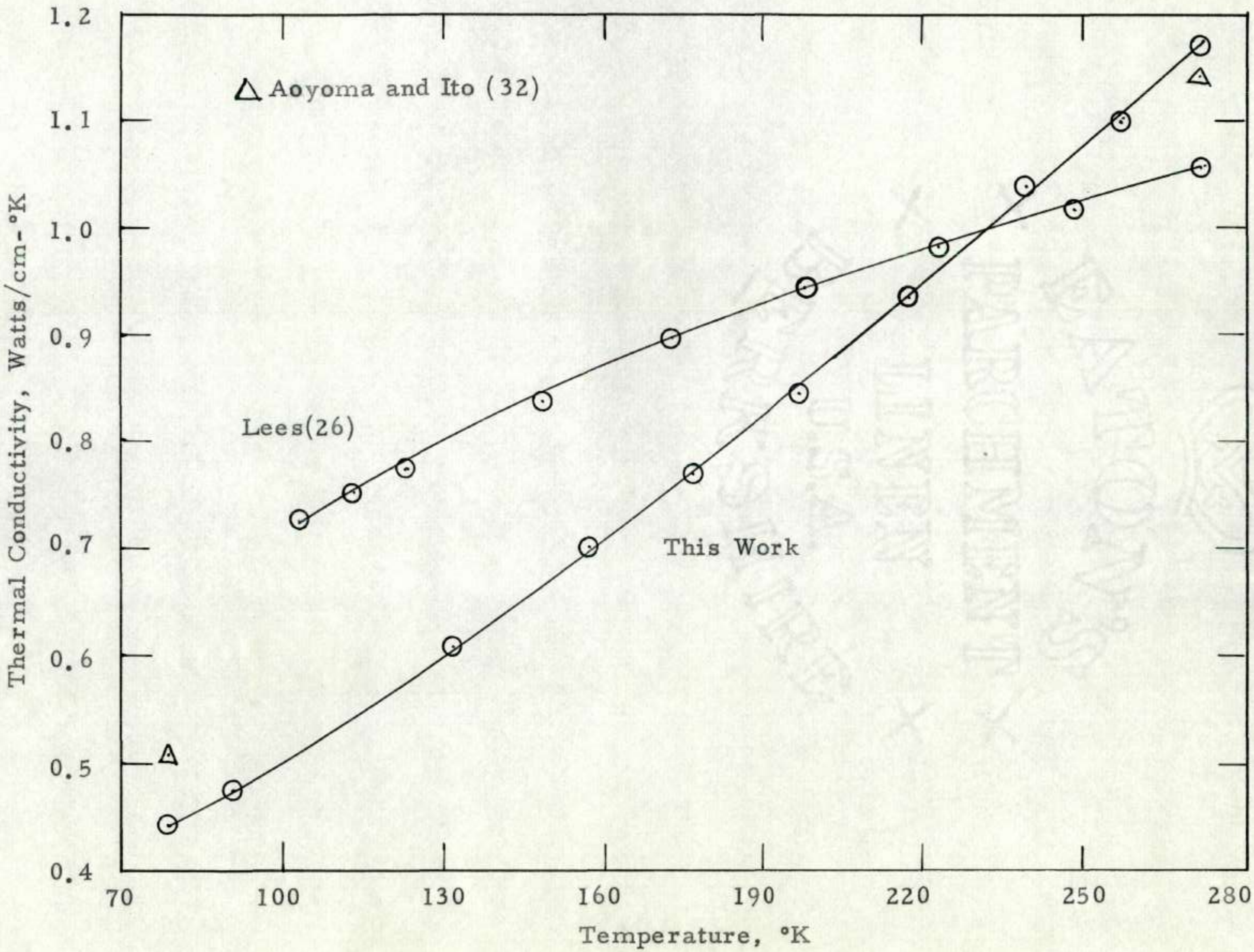


Figure 9

Thermal Conductivity of Brass

TABLE 2

Thermal Conductivity of Brass

Explanation:

Tm	=	Temperature of copper block + 1/2 Δ Tm, °K
Q_1	=	Heat supplied by heater, watts
Q_0	=	Q_1 corrected for loss through leads, watts
ΔTm	=	Temperature difference, head to copper block, °C
ΔTc	=	ΔTm - ΔTg -0.02°C
ΔTg	=	Temperature drop across Vaseline film
k	=	Thermal conductivity calculated with ΔTm and Qo
k'	=	Thermal conductivity corrected for rise in temperature during measurement, watts/Cm°C

Tm	Q_1	Q_0	ΔTm	ΔTc	k	k'
79.88	0.03287	0.03285	2.37	2.35	0.442	0.434
92.40	0.03598	0.03596	2.40	2.38	0.477	0.470
113.36	0.03972	0.03970	2.31	2.29	0.548	0.542
133.44	0.04394	0.04392	2.38	2.26	0.615	0.610
158.78	0.04388	0.04387	1.97	1.95	0.710	0.708
177.60	0.05321	0.05320	2.19	2.17	0.776	0.774
198.01	0.05425	0.05424	2.02	2.00	0.856	0.855
217.34	0.06731	0.06730	2.28	2.28	0.943	0.940
240.84	0.06876	0.06875	2.09	2.07	1.05	1.05
256.64	0.07935	0.07934	2.29	2.27	1.11	1.11
275.36	0.07796	0.07796	2.11	2.09	1.18	1.18

The thermal conductivity of cadmium. --The thermal conductivity of cadmium was found to be 0.940 at 81°K, 0.914 at 114°K and 1.05 watts/cm°C at 276°K with the same estimated error and corrections discussed for brass. The minimum at 114°K was somewhat unexpected as it had not been previously reported. Theory, reported results of other workers and comparison with other metals indicate that the conductivity should decrease as the temperature increases. Lees' (26) results, plotted in Fig. 10, show a steady increase in conductivity with decrease in temperature. His work is corroborated to a certain extent by other investigators (1). The results obtained here cannot be satisfactorily explained by poor thermocouple calibration because the thermocouple potential-temperature curve has the expected characteristics and no anomalies appeared in the results for brass. Unpublished work of W. D. Bradbury, Jr., and M. H. Cooper carried out at the Georgia Institute of Technology since these measurements were made indicate that the calibration of TCD-1 (used with cadmium) may be 8-10 per cent low in the range 80 to 140°K, but the indicated correction will not remove the minimum.[1] A few metals of high purity exhibit a behavior similar to the cadmium used in these experiments (88, Table I).

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[1] Subsequent work by M. H. Cooper at the Georgia Institute of Technology indicates that the calibration of TCD-2 (used for brass) is more accurate than TCD-1 (used for cadmium) and that the results for brass are probably accurate to within 5 per cent, cadmium within 10 per cent.

A slightly impure slightly strained metal may have a minimum in its temperature-conductivity curve.

Final results for cadmium will be found in Fig. 10 and Table 3.

The thermal conductivity of copper and vaseline. --The thermal conductivity of the copper specimen used in the calibration run can be determined by measuring the heat delivered to the specimen while a temperature gradient exists along the specimen. If the conductivity so determined agreed well with published values an excellent check on the calibrations and the method would be obtained. The results, so calculated, however, did not agree well with published results and it was then decided to measure the temperature drop across the Vaseline film and correct the calibrations as necessary. The temperature drop across the Vaseline film was measured in the experiments on cadmium and brass. The installation, calibration and use of the thermocouples made for this purpose is described above.

In the experiments on brass and cadmium, the rate of heat transfer and the temperature drop across the Vaseline film was measured and the area of the Vaseline film calculated from the length and diameter of the copper contactors. The thermal conductivity of the Vaseline could then be calculated if its thickness could be estimated.

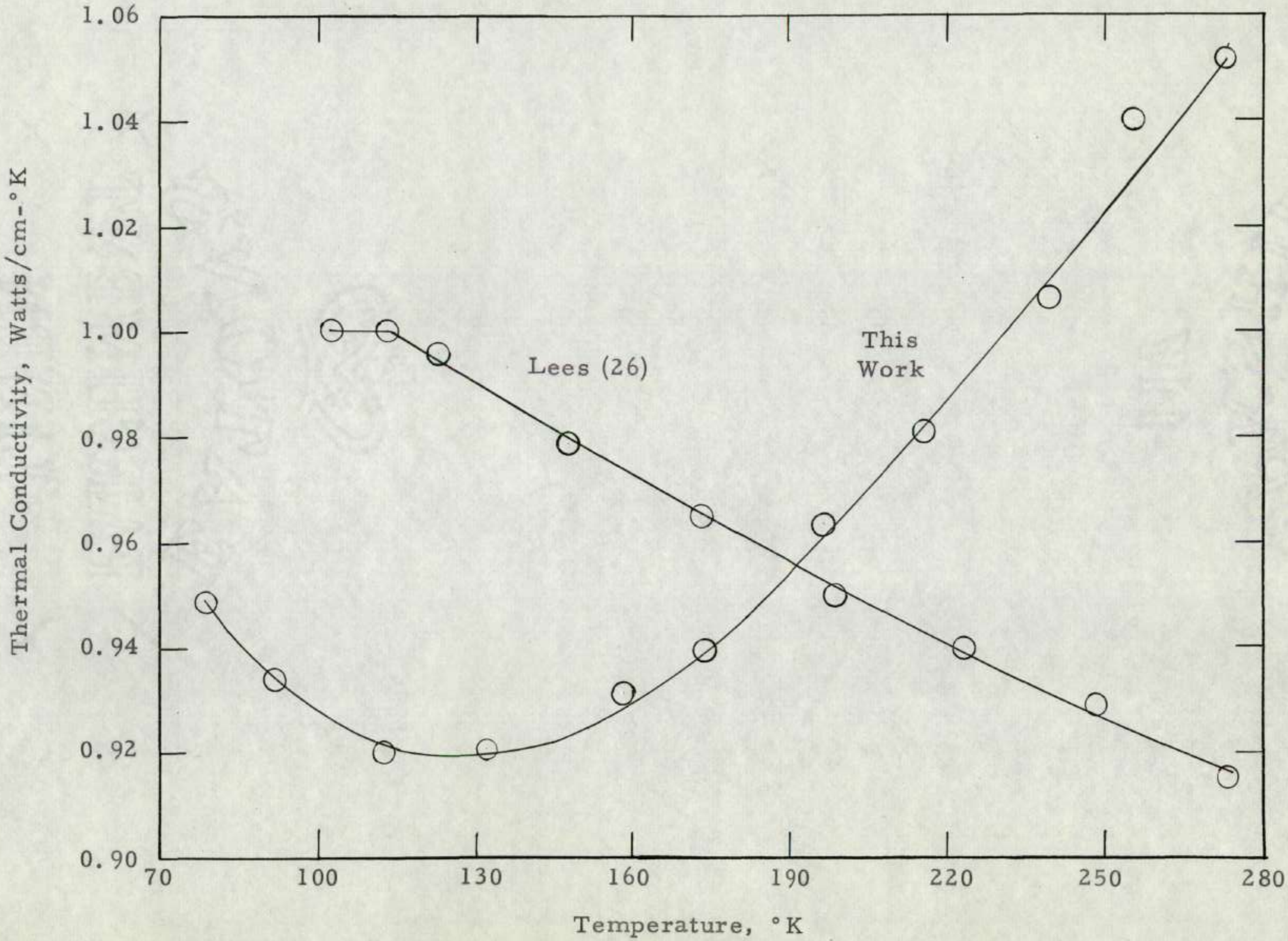

Figure 10

Thermal Conductivity of Cadmium

TABLE 3

Thermal Conductivity of Cadmium

Explanation:

See Table 2

Tm	Q_0	Qc	ΔTm	ΔTc	k	k'
81.51	0.07722	0.07720	2.62	2.60	0.955	0.940
92.83	0.07736	0.07734	2.66	2.64	0.941	0.926
113.92	0.07538	0.07536	2.63	2.61	0.927	0.914
133.64	0.06799	0.06797	2.37	2.35	0.929	0.918
159.26	0.07335	0.07334	2.53	2.51	0.938	0.930
177.79	0.06956	0.06955	2.38	2.36	0.947	0.941
198.18	0.06512	0.06511	2.17	2.15	0.973	0.966
217.36	0.07093	0.07092	2.32	2.30	0.990	0.985
241.08	0.07440	0.07439	2.35	2.33	1.03	1.03
256.73	0.07317	0.07316	2.26	2.24	1.05	1.05
275.62	0.08000	0.07999	2.44	2.42	1.06	1.05

Since the holes in the copper block and the copper contactors were both accurately machined it seemed reasonable to estimate the film thickness as 0.001 ± 0.0005 inch. The thermal conductivity of the Vaseline film, calculated on this basis, is plotted in Fig. 11 and tabulated in Table 10 in the Appendix. It will be noted that the conductivity as measured on the brass specimen reaches a rather sharp maximum at about 117°K whereas the curve of conductivity as measured with the cadmium specimen versus temperature is much more regular. Examination of the data in Table 7 shows that the thermocouple potentials for the brass specimen are smallest, and therefore have the largest likely error, in the temperature range where the deviation is greatest. The possibility of error is about the same for both specimens above 176°K and the curves agree best in this region. The data obtained from the cadmium specimen was therefore chosen to correct for the temperature drop across the Vaseline film on the copper specimen. Sample calculations for the conductivity of Vaseline and copper are included in the Appendix.

The thermal conductivity of the copper specimen, which was turned down from a single piece of commercially available copper rod, was calculated after correcting for temperature drop across the Vaseline film. The results are shown in Fig. 12 and Table 11 in

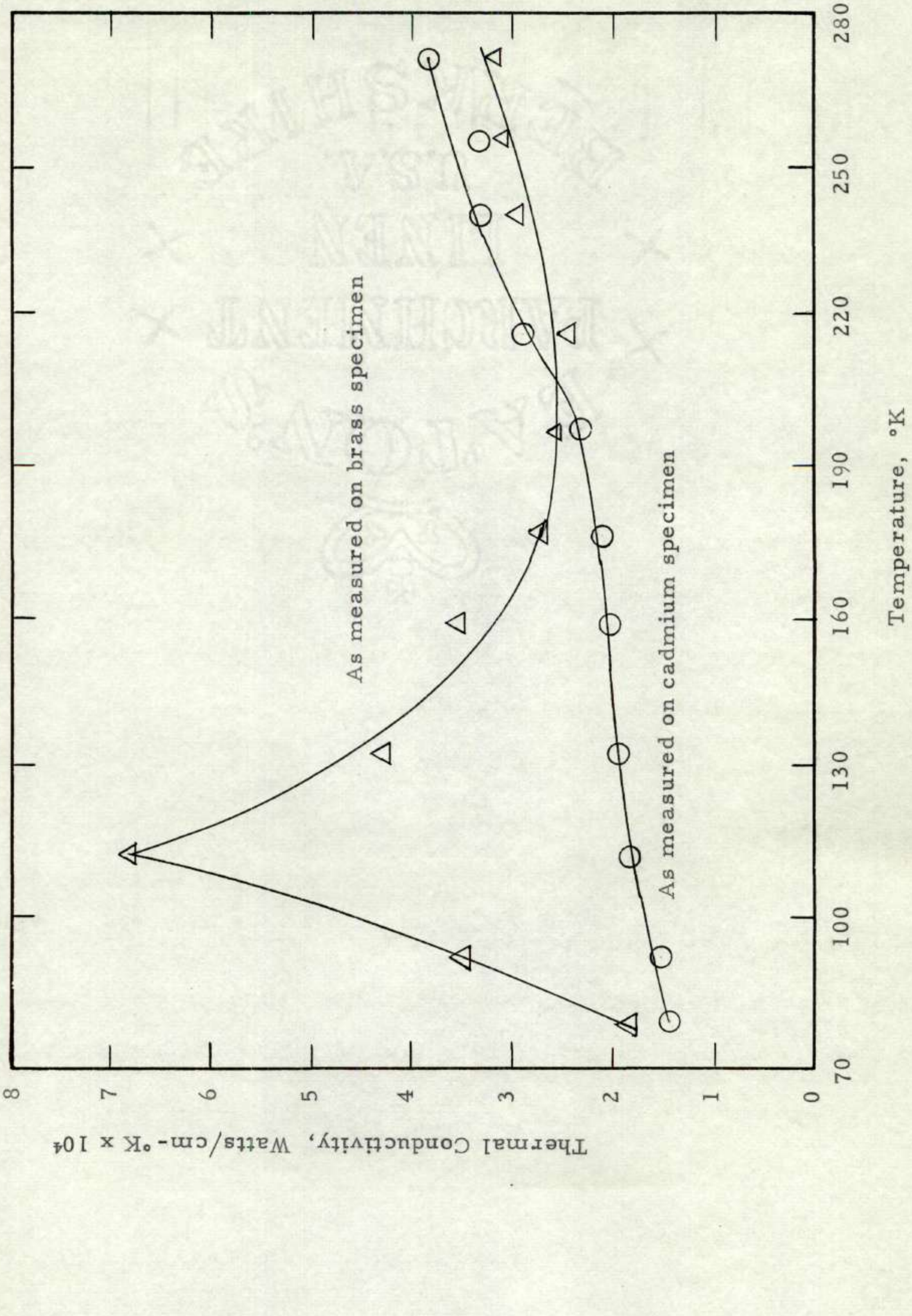

Figure 11

Thermal Conductivity of Vaseline

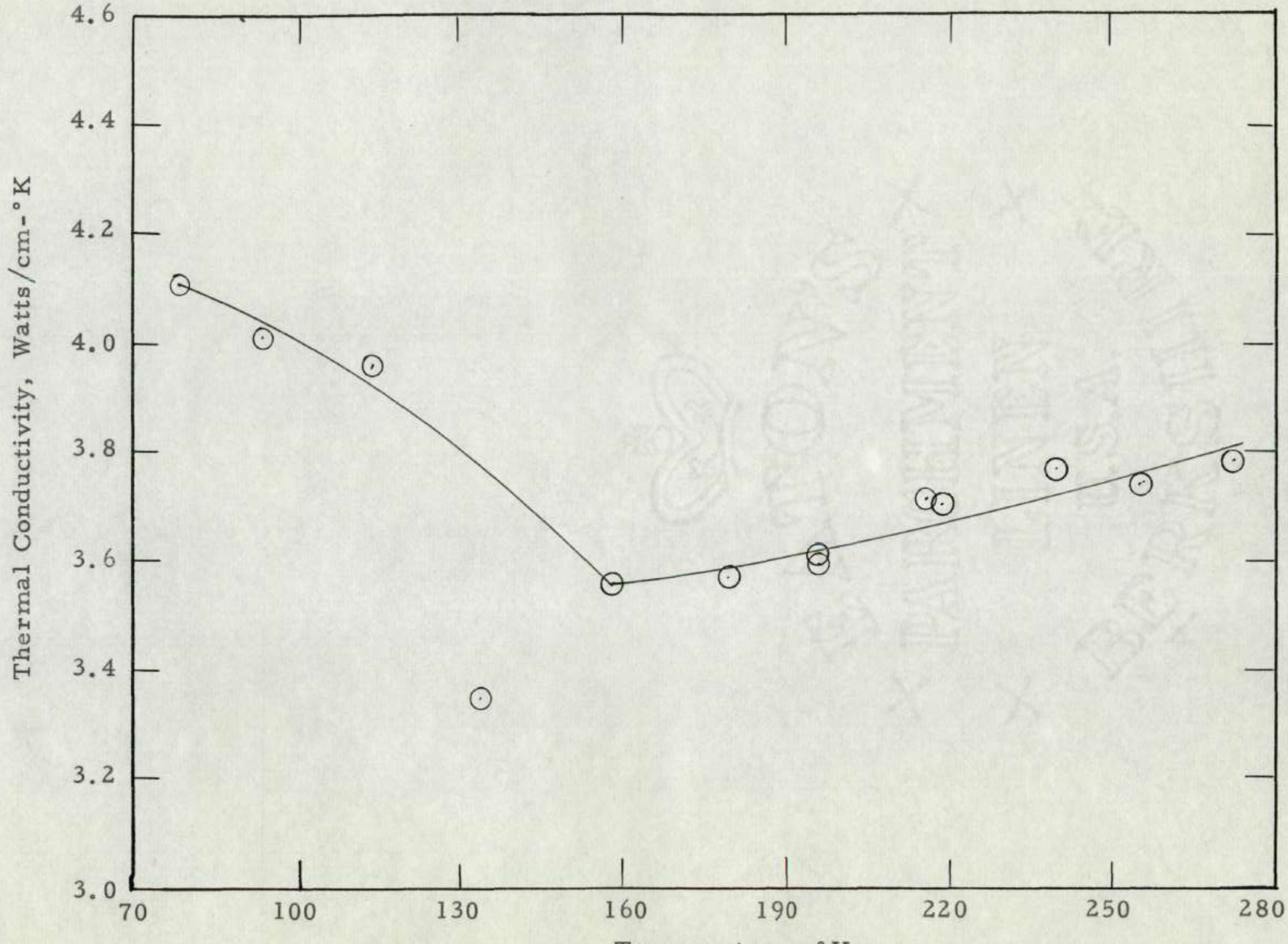

Figure 12

Thermal Conductivity of Copper

the Appendix. The conductivity at all temperatures is too low and in fact reaches a minimum at 134°K. This is probably due to failure to reach thermal equilibrium in the system. The supply of refrigerant was limited and the experiment was probably rushed too much. This does not invalidate the calibration of the thermometer and thermocouples, however. The calibration run was stopped temporarily at about 236°K and later continued with a dry ice-alcohol bath at about 200°K. Two calibration points were repeated and good agreement with previous results obtained.

Accuracy of the work. --Errors may be introduced from the following sources:

(a) Reading of the instruments;

(b) Heat transfer by radiation;

(c) Heat flow pattern in the heads;

(d) Manner of attaching thermocouples;

(e) Corrections to zero readings of thermocouples;

(f) Failure to attain equilibrium in the calibration experiment;

(g) Temperature rise of specimen and head during experiment.

It can be shown that the error due to reading the instruments is less than one per cent. This is not a large fraction of the total error.

Heat transfer by radiation from the specimen to the copper block is estimated to be less than one per cent at 273° K and decreases rapidly as the temperature is lowered. It is therefore considered insignificant.

The flow of heat along the head induces a temperature gradient. Due to the fact that the thermocouples were not attached at the head-specimen boundary, they will not read the true temperature difference and a correction is necessary. This gradient is estimated to be such that the thermocouples read about 0.015° C high for the calibration head and 0.02° C high for the brass and cadmium heads (see sample calculations). The heat flow pattern in the region of the head-specimen interface is unknown and no correction can be made for this effect. The resulting error is probably less than two per cent, however.

The thermocouples were attached in the calibration runs to the copper block and calibration head by small copper bridges which were soldered to the copper block or head. The elasticity of these bridges was expected to provide sufficient tension to maintain good thermal contact between the thermocouple and copper block or head. It is felt that this is not the best method as there may not be enough tension for good contact and the soldered joint may fail. The ends of the junctions were soldered directly to the brass and cadmium heads.

This is a better solution. However, the scheme of mounting the ends of the couple in an electrically insulated copper sheath is open to the objection that it offers a rather high resistance to the passage of heat and consequently the junction may be at a temperature somewhat lower than the body to which it is attached. It would be preferable to mount each junction individually. The magnitude of these effects is unknown, but believed to be small.

It was found experimentally that in the calibration experiment the thermocouples did not read zero when the head and copper block were presumably at the same temperature, but usually indicated that the head was at a slightly lower temperature than the block. This led to a correction to the thermocouple potential which was usually positive and ranged up to 10 per cent of the potential reading. The error introduced was small, however, as evidenced by the fact that the corrections at 197°K and 216°K were about 10 per cent of the thermocouple reading with a liquid nitrogen bath and almost negligible when the calibration was repeated with a dry ice-alcohol bath; good agreement between the two readings was obtained at both temperatures. The maximum error from this source is probably not larger than 5 per cent.

Failure to attain equilibrium probably affected the calibration experiment. This was due primarily to the high thermal conductivity of the copper "specimen". The quantity of heat required to maintain the desired temperature difference was so large that the temperature of the copper block was increasing rather rapidly, 0.003°C to 0.009°C per minute, especially at low temperatures where the heat capacity of copper is lowest and its thermal conductivity highest. Under these conditions the resistance of the thermometers was changing so rapidly that it was difficult to measure, and also difficult to measure the drift rate. This difficulty was not encountered with brass and cadmium due to their lower conductivity. It should be noted that this error does not invalidate the thermocouple calibrations. The error from this source is probably only a few per cent.

In the course of the experiment it was found that when steady-state conditions were reached the temperature of the copper block, specimen and head increased gradually with time, while the difference in the temperature of the head and the block remained virtually constant. This observation led to the conclusion that heat was being stored in the head and specimen and a correction would be necessary. Reference to Tables 8 and 9 shows that this correction is less than two per cent of the value of the thermal conductivity and that it decreases as the temperature increases. The method for calculating this correction is explained in the Appendix.

It is somewhat difficult to determine a definite value for the error involved in these measurements. It is felt that the maximum error inherent in the experiment as performed is about 10 per cent, and that the results are sufficiently accurate for most engineering purposes.

Conclusions and recommendations. --The apparatus as described can be used successfully to measure the thermal conductivity of metals and alloys, provided the conductivity of the specimens chosen is not too large or too small. The range of conductivity over which acceptable results can be obtained is roughly between 0.2 and 1.5 watt/cm °C, although actual measurements are necessary to determine the range exactly. The temperature of the head and the copper block seem to increase at the same rate to maintain a constant temperature difference once equilibrium has been attained. About 15 - 20 minutes are required to reach equilibrium.

The experiment could be improved by attaching the thermocouple junctions individually to the specimen itself at some point below the head and above the copper contactor. This would eliminate the unknown interface effects discussed above. The calibration experiment could be improved by substituting a specimen of lower thermal conductivity, such as aluminum, magnesium or an alloy such as brass or bronze, for the copper used in this work. Measurements between 80°K and 275°K with error less than 5 per cent should be obtained without difficulty.

APPENDIX

DERIVATIONS

General equation for heat conduction. --The quantity of heat which will flow through a solid body in a given time depends on the nature of the material, the temperature gradient and the nature of the specimen. Consider the elemental cube of Fig. 13 through which a differential quantity of heat is flowing in the X direction only. The heat which flows in, dq_1, may be equal to, greater than or less than the heat, dq_2, which leaves the specimen. Either of the last two cases is more general as a storage or depletion of heat is entirely possible. It is readily shown that the total heat, dq, conducted in the element in a differential time and including the variation of temperature gradient with respect to both time and position in the cube is

$$\frac{dq}{dt} = k \; dA \; \frac{\partial^2 T}{\partial x^2} \, dx = Cp \; \rho \; dx \; dy \; dz \; \frac{\partial T}{\partial t} \tag{14}$$

Removing the restriction of unidirectional heat flow and assuming a homogeneous and isotropic material, equation (14) becomes

$$\frac{\partial T}{\partial t} = \frac{k}{\rho \, Cp} \left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right] \tag{15}$$

which is Fouriers general equation for heat conduction.

The experimental work reported in this thesis was performed under steady-state conditions with unidirectional heat flow in a specimen of constant cross section. Under these conditions $dT/dt = 0$, $\partial T/\partial x$

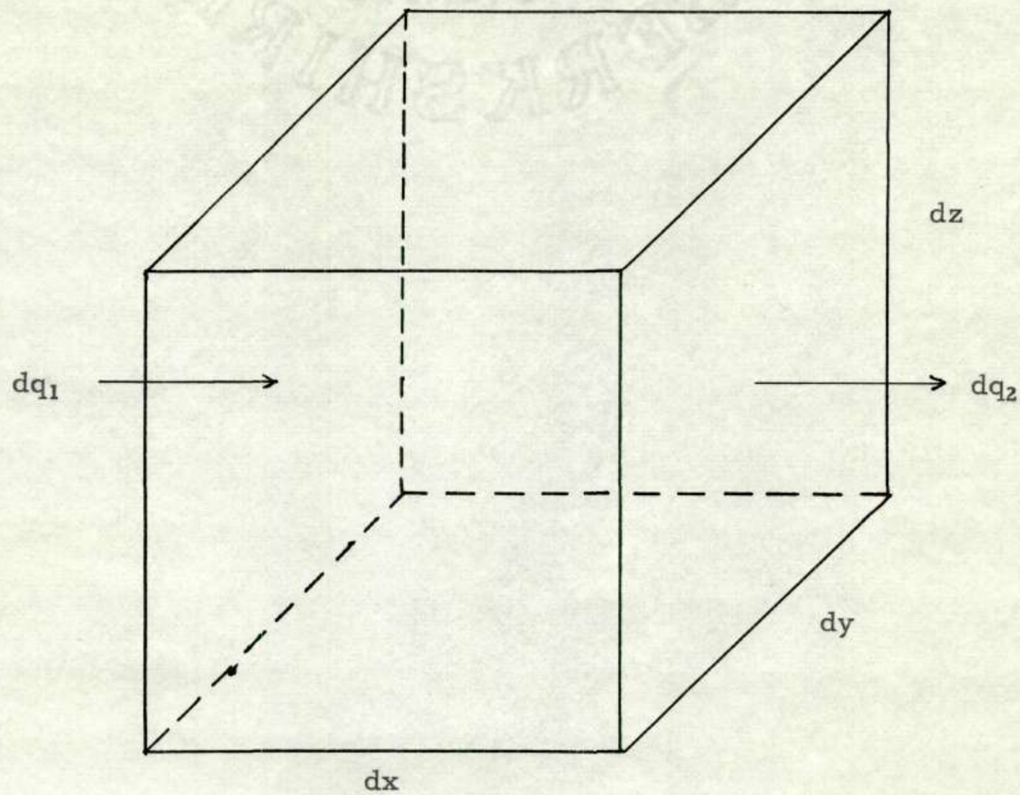

Figure 13

Model for Heat Conduction

is constant and $\partial^2 T/\partial x^2 = 0$, q is constant and dA can be replaced by A. Since the thermal conductivity is substantially constant over a small temperature range, dT/dx can be replaced by $\Delta T/L$. and equation (14) becomes

$$\frac{q}{t} = Q = \frac{kA\,\Delta T}{L} \tag{12}$$

This equation corrected for the experimental arrangement is the basis for the experiments reported herein. The corrections will now be discussed.

Correction due to temperature rise during experiment. --It was found in the course of the experiment that the temperature of the copper block and specimen head increased at a slow rate under the experimental conditions. This requires the storage in the specimen and its head of a certain fraction of the total heat input and gives rise to a correction to the thermal conductivity measurements. Since dT/dt is not zero equation (14) applies and we have

$$\frac{dT}{dt} = \alpha \frac{\partial^2 t}{\partial x^2} \tag{16}$$

where $\alpha = k/\rho\, Cp$. Equation (16) defines the change of temperature with time, or the drift rate, of any point x in a rod.

In this experiment dT/dt is substantially constant, and $(dq/dt)_x = Q_x = -kA\,(dT/dx)_x$ at any cross section x in a rod. Substituting the drift rate, a, into equation (16), integrating and solving for the constant of integration, there results

$$Q_x = -aACp\rho_x - kA\left(\frac{T_1 - T_2}{x_1 - x_2}\right) + \frac{aACp}{2} \quad (x_1 + x_2) \tag{17}$$

Note that at $x = x_1$, $Q_x = Q_{x_1}$ and that $A\rho(x_1 + x_2)/2 = (A\rho/2)$ $(2x_1 + x_2 - x_1)$, and $A\rho(x_2 - x_1) = (M)_{x_2 - x_1}$, the mass of the rod under consideration. Making these substitutions in equation (17) and solving for k we have

$$k = \frac{Q_{x_1}(x_2 - x_1)}{A(T_1 - T_2)} \left[1 - \frac{a}{2Q_{x_1}} \quad (Cp(M)_{x_2 - x_1})\right] \tag{18}$$

If Q_0 is the heat supplied to the heater less the small amount conducted through electrical leads, and if dT/dt is constant for head and specimen,

$$Q_{x_1} = Q_0 - q \tag{19}$$

$$q = a \ C_H M_H + C_s(M)_{0-x_1} \tag{20}$$

where C_H and C_s are the specific heat of the head and specimen, respectively, M_H is the mass of the head and $(M)_{0-x_1}$ is the mass of the specimen above the point under consideration. $(M)_{0-x_1}$ is zero in this experiment. Substitution of equation (19) into (18) gives

$$k = \frac{Q_0(x_2 - x_1)}{A(T_1 - T_2)} \left[1 - \frac{a}{Q_0}\left(\frac{q}{a} + \frac{C_s}{2} \ (M)_{x_2 - x_1}\right)\right] \tag{21}$$

where the symbols are summarized as follows:

Q_0 = heat supplied to head (corrected for loss or gain along leads), watts

q = $(C_H M_H + C_s (M)_{0-x_1}) a$

a = drift rate, °C/min

x_2-x_1 = effective length of specimen, cm

$T_1 - T_2$ = temperature difference across the length x_1-x_2, °C

A = cross sectional area of specimen, cm^2

$M_{x_2-x_1}$ = mass of specimen, gm

M_{0-x_1} = mass of specimen above x_1 (=0 in this case)

M_H = mass of head, gm

C_s, C_H = heat capacity of specimen and head, respectively, joules/gm-°C

This completes the derivations which are too long or too general to be included in the sample calculations, which follow.

SAMPLE CALCULATIONS

The calibration experiment consisted of taking three sets of readings at each calibration point. In the equilibrium period preceeding and following each "thermal conductivity" measurement the two thermometer resistances and the potential of both thermocouples were recorded as a function of time. In the "thermal conductivity" measurement made at each calibration point the resistance of both thermometers, the potential of both thermocouples, and the amperage and voltage drop across the heater were recorded as a function of time. Since there was a measurable change of most of these quantities with time it was necessary to know their value at some arbitrarily chosen reference time. A similar situation existed in the experiments on brass and cadmium. The methods for making these computations will be shown by example.

Calibration of the copper thermometer. --These calculations require three steps: (1) calculation of each thermometer resistance from the resistance of the two circuits at an arbitrarily chosen reference time; (2) suitable extrapolation and/or interpolation to find the resistance of the two thermometers at another arbitrarily selected reference time; and (3) conversion of the platinum thermometer resistance to temperature at the latter reference time. This temperature corresponds to the resistance of the copper thermometer at the same time. Typical raw data for one equilibrium measurement in Table 4 and derived resistance and temperatures for one set of measurements in Table 5 will be used to illustrate in detail the procedures followed. It will be assumed that all changes are linear with respect to time.

The first reference times chosen are indicated in Table 4 by an asterisk. Take for example the time 9:50:00. The "N" circuit resistance is 24.2866 ohms, but the galvanometer is not reading zero so a correction is necessary. The magnitude of the correction depends on the sensitivity of the galvanometer, which was measured at 9:50:30 when the resistance in the circuit was decreased 0.001 ohms. The galvanometer reading at this time was 18.50 cm. The reading 10 seconds earlier was 21.20 cm, but this reading must be corrected for drift rate. The drift rate is (21.20 - 21.08) cm per 20 sec. or 0.12 cm/20 sec. The galvanometer reading, with 24.2866 ohms in the circuit, at 9:50:30 would be $21.20 + (0.12/20) \times 10 = 21.26$ cm. The sensitivity is now seen to be $(21.26 - 18.50) = 2.76$ cm per 0.001 ohm. The resistance at the reference time, 24.2866 ohms, can now be corrected for non-zero galvanometer reading. The resistance is then $24.2866 + (21.40 - 21.08)/(2.76 \times 10^3) = 24.28675$ ohms.

TABLE 4

Raw Data for Thermometer Resistance

Time	Resistance	Galv. Reading	Sens.	Zero Reading
9:48:20	R 24.0657	21.05		
:40		21.18		
:50	24.0647	19.45	1.80	21.00
:50:00*	N 24.2866	21.08		
:20		21.20		
:30	24.2856	18.50	2.76	21.40
9:51:40	N 5.0248	20.10		
:52:00		20.25		
:20	5.0258	23.60	3.20	20.40
:53:15*	R 5.1155	20.50		
:35		20.51		
:50	5.1165	24.20	3.68	20.92
9:55:45	R 24.0697	20.70		
:56:05*		22.40	1.80	21.10
:57:00	N 24.2809	20.95		
:20		20.60	2.76	21.40

Notes:

Resistance in ohms.
Galvanometer reading in centimeters.
Sensitivity in centimeters per 0.001 ohms.
Asterisk indicates reference time at which resistance of thermometer is calculated.
R is resistance on "R" circuit of temperature bridge; N is resistance on "N" circuit.

TABLE 5

Resistance Data at about -54° C

Time	R_{Th-2}	R_{Cu}	R'	T_{Th-2}°C	Drift Rate Th-2	Drift Rate Cu
Equilibrium:						
9:50:00	24.17571					
9:53:15	(24.17508)	5.07000	0.778027	-54.218		
9:56:05	24.17453				1.7	0.10
9:58:40	(24.17391)	5.06984	0.777989	-54.227		
10:01:20	24.17329					
Head heater on:						
10:30:20	24.24432					
10:34:40	(24.26009)	5.15626	0.780832	-53.539		
10:37:00	24.26859				31.0	2.6
10:43:45	(24.29384)	5.16318	0.781946	-53.269		
10:45:20	24.29976					
Equilibrium:						
11:12:45	24.50925					
11:14:20	(24.50900)	5.14613	0.789045	-51.550		
11:17:50	24.50845				1.3	0.13
11:19:35	(24.50817)	5.14593	0.789018	-51.556		

Notes:

R_{Th-2} is resistance of platinum thermometer, R_{Cu}, the copper thermometer.

R' is the ratio of the resistance (Th-2) at T° C to that at 0° C.

Drift rate is the rate of change of temperature in millideg C/min.

In similar fashion the resistance of the "R" circuit is found at 9:50:00. In this case the sensivity is 1.80 cm per 0.001 ohm and the drift rate is +0.13 cm per 20 sec. The galvanometer reading must be extrapolated from 9:48:20 to 9:50:00, or 100 sec. If a linear relationship is assumed the galvanometer reading is 21.05 + (0.13/20) x 100 = 21.70. The "R" circuit resistance is then 24.0657 - $(21.70 - 21.00)/(1.80 \times 10^3)$ = 24.06531 ohms.

The true resistance is the arithmetic average of the "N" and "R" resistances plus corrections for instrument zero and dial settings. These corrections should properly be applied to the individual resistances but they are quite small and no significant error is introduced by applying them to the average. The true resistance in this case is then (24.0531 + 24.28675)/2 = 24.17603 plus the following corrections:

	24.17603	
+	0.00001	(instrument zero correction)
-	0.00032	(corrections for dial settings)
	24.17572	ohms

All individual thermometer resistances were calculated in a similar manner.

It is now necessary to find the resistance of both thermometers, measured in an equilibrium period, at the same reference time. Linear interpolation or extrapolation is again used. For example, the resistance of the platinum thermometer, Th-2, is found at 9:58:40 (Table 5) to be 24.17391. This is the resistance of the platinum thermometer which corresponds to a resistance of 5.06984 ohms on the copper thermometer, and when the temperature of the platinum thermometer is known one calibration point for the copper thermometer will be established.

The conversion of platinum thermometer resistances to temperature was done by the method of Werner and Frazer (85) for temperatures above 83°K. Mr. R. G. Wooten made the conversion for temperatures below 83°K using the method of Los and Morrison (86). Equation (22) and the tables of Werner and Frazer were used to convert resistance to temperature (°C):

$$R' = R\,(0.03299514) - 0.019633 \qquad (22)$$

Where R = the resistance to be converted, $R' = R/R_o$ and R_o = the resistance at 0°C. For the resistance just calculated,

$$R' = 24.17391\ (0.03299514) - 0.019633 = 0.777989 \qquad (23)$$

From the tables of Werner and Frazer, interpolating linearly, this R' corresponds to a temperature of -54.227°C. Since this was an equilibrium measurement, the resistance of the copper thermometer at -54.227°C is 5.06984 ohms. This constitutes one calibration point for the copper thermometer. The complete calibration will be found in Table 6.

TABLE 6

Calibration of Copper Thermometer

Symbols:

R - Th-2	- the resistance in ohms of the standard thermometer
R - Cu	- the resistance in ohms of the copper thermometer
T°K	- the temperature corresponding to the resistances in degrees Kelvin
D	- drift rate of copper block, (Temp. decreasing)

R - Th-2 ohms	R - Cu ohms	T°K	D Millideg C/min.
5.94197	0.96385	78.217	0.6
6.40220	1.05775	81.642	0.4
7.68449	1.32855	91.156	0.7
8.59046	1.52554	97.928	1.5
10.55675	1.96469	112.741	4.0
11.28328	2.12908	118.253	2.5
13.16083	2.55677	132.586	9.3
13.22670	2.57156	133.095	8.1
16.31836	3.27780	156.978	3.3
16.77902	3.38350	160.563	4.4
18.77254	3.83864	176.520	5.4
19.30856	3.96089	180.363	3.5
21.34946	4.42617	196.490	4.7
21.35140	4.42737	196.484	0.5
21.72736	4.51296	199.463	0.6
21.77476	4.52334	199.839	3.4
23.71101	4.96426	215.238	3.3
24.08879	5.05085	218.252	0.0
24.17391	5.06984	218.933	1.7
24.50900	5.14613	221.610	1.3
26.68670	5.64214	239.073	3.0
27.29022	5.77979	243.931	1.4
28.52879	6.06259	253.923	2.9
28.61344	6.08161	254.607	3.9
30.93784	6.61491	273.447	-
31.35137	6.70937	276.810	0.4
33.32011	7.16127	292.866	-
34.42558	7.41738	301.951	0.5
34.62612	7.46325	303.559	0.2

Calibration of three junction copper-constantan thermocouples. -- The next step is the calibration of the copper-constantan thermocouples. A temperature, a temperature difference and the potential developed by the thermocouples are required. The temperature used was that of the copper block, measured by Th-2, plus one-half the temperature difference between the copper block and the head. The temperature difference was found in the following manner. In the calibration experiment, three series of measurements were taken at each calibration point: the first at equilibrium; the second with the head heater on and a Δ T of 2° to 3°C maintained; and another at equilibrium at approximately 3°C higher than the first. Now, the temperature of the copper block was measured with Th-2 and the temperature of the head, with the heater on, can be calculated by assuming a linear variation of the resistance of the copper thermometer with temperature over the small temperature range involved. This assumption was later verified by plotting resistance versus temperature and obtaining a straight line (see Fig. 7). The procedure is illustrated in equations (24), using data from Table 5.

$$\frac{5.14613 - 5.06984}{-51.550 + 54.227} = \frac{5.15626 - 5.06984}{T + 54.227} \qquad (24A)$$

$$T = \frac{2.677}{0.07629} (0.08642) - 54.227 = -51.195°C \qquad (24B)$$

where T = the temperature of the head. Then Δ T = -51.194 + 53.539 = 2.345°C.

The thermocouple potential was read directly on the White Double Potentiometer. The mechanics of correcting the potentiometer reading for non-zero galvanometer readings and to a common time is in every respect similar to that used for the thermometer resistances. For this particular point, the thermocouple potentials are 191.1 microvolts for TCD-1 and 198.3 for TCD-2. These potentials divided by the temperature difference (2.345°C in this case) completes the calibration of the thermocouples. The complete calibration will be found in Table 7 and Fig. 8.

There is an error in the thermocouple calibrations which can be estimated. It can be seen in Fig. 4 that the copper thermometer was located between the heater and the thermocouples. There will be a temperature gradient in the head due to conduction of the heat input to the heater. This gradient can be approximated by equation (12), where $Q_0 = 0.28$ watts, $k = 4.0$, $L = 0.5$ inch, and $A = (\pi/4)(0.75 \text{ in.})^2$. Then

$$\Delta T = \frac{0.28}{4.0} \times \frac{4 \times 0.5}{\pi (0.75)^2 (2.54)} = 0.031°\text{C} \qquad (25)$$

The copper thermometer may therefore indicate a temperature that is approximately $0.031/2 = 0.015°$C higher than that at the thermocouple junction. This leads to an error of approximately 0.5 per cent at 80°K, becoming less as the temperature increases.

TABLE 7

Calibration of Three-Junction Thermocouples

Explanation:

T_B	- Temperature of copper block + 1/2 ΔT_m
ΔT_m	- Temperature difference, head to copper block
EMF	- Thermocouple potential
Equil.	- Equilibrium measurement
k meas.	- "Thermal conductivity" measurement
Corr	- Correction applied to thermocouple EMF
$\frac{(EMF)_c}{\Delta T}$	- Thermocouple sensitivity

		EMF during				$\frac{(EMF)_c}{\Delta T}$
T_B °K	ΔT °K	Equil. Micro-volts	k meas Watts $Cm^{-1} deg^{-1}$	Equil. Micro-volts	Corr Micro-volts	Micro-volts deg^{-1}
TCD-1, Liquid nitrogen bath						
80.25	2.90	0	122.5	+0.2	-0.1	42.21
95.49	2.78	0	131.0	0	0	47.07
115.76	2.91	-1.0	156.6	-1.5	+1.2	54.19
135.64	2.88	-2.0	178.3	-1.0	+1.5	62.39
159.56	2.72	-4.6	178.7	-4.5	+4.5	67.48
181.65	2.50	-7.5	175.0	-6.8	+7.2	72.76
198.44	2.47	-8.3	184.3	-5.0	+6.6	77.38
217.37	2.34	-6.8	189.2	-5.0	+5.9	83.38
TCD-1, Dry ice-alcohol bath						
198.61	2.42	-0.05	189.4	-0.75	+0.4	78.30
220.96	2.33	-5.0	191.1	-4.0	+4.5	83.98
240.94	2.28	-8.5	196.0	-8.3	+8.4	89.77
256.44	2.29	-9.8	200.4	-6.5	+8.2	91.17
275.46	2.52	0	253.6	0	0	100.63
291.74	2.47	+1.2	257.7	+4.0	-2.6	103.11
303.72	2.43	+0.8	260.4	+1.1	-1.0	106.66

TABLE 7 (Continued)

Calibration of Three-Junction Thermocouples

T_B °K	ΔT °K	EMF during Equil. Micro-volts	k meas Watts $Cm^{-1} deg^{-1}$	EMF during Equil. Micro-volts	Corr Micro-volts	$\frac{(EMF)_c}{\Delta T}$ Micro-volts deg^{-1}
TCD-2, Liquid nitrogen bath						
80.25	2.90	0	126.8	+0.2	-0.1	43.69
95.49	2.78	0	135.7	0	0	48.76
115.76	2.91	0	163.1	-0.5	+0.2	56.08
135.64	2.88	-0.2	186.7	+1.0	-0.4	64.64
159.56	2.72	-0.5	190.0	-0.5	+0.5	70.50
181.65	2.50	-1.5	187.9	-1.5	+1.5	75.64
198.44	2.47	-2.0	198.0	-0.5	+1.2	80.74
217.37	2.34	-2.3	200.5	-2.0	+2.2	86.62
TCD-2, Dry ice-alcohol bath						
198.61	2.42	-0.05	194.2	-0.7	+0.4	80.28
220.96	2.33	-2.5	198.3	-1.5	+2.0	86.00
240.94	2.28	-4.9	204.3	-4.3	+4.6	91.74
256.44	2.29	-6.0	208.8	-4.0	+5.0	93.44
275.46	2.52	0	255.7	0	0	101.47
291.74	2.47	+1.2	260.2	+3.0	-2.1	104.41
303.72	2.43	+0.8	262.0	+0.7	-0.8	107.40

No correction for this effect was made in calculating the thermocouple sensivity, but it is, of course, included in the estimated error of the measurements.

Thermal conductivity of brass and cadmium. --These calculations are based on equation (21) with corrections as discussed below. The length of the specimens was measured with an adjustable parallel bar and the diameters with a micrometer. The exact dimensions are given in Fig. 5. The heat input to the specimens, Q, was measured on the White Double Potentiometer as the voltage drop across a 1.0000 ohm standard resistance, giving the amperage, I, directly, and as 1/100 of the voltage drop, E, across the heater, the reduction in voltage occurring in a volt box. Then

$$Q = 100\,E\,I \tag{26}$$

The calculation of Q is a straight forward substitution in equation (26). However, a fraction of the heat was conducted to the copper block along the heater and thermocouple leads. The heat so lost was calculated from the length, size and thermal conductivity of the leads and the ΔT between the head and the copper block. The corrections are recorded in Tables 2 and 3.

r

The temperature drop across the specimen was measured by two thermocouples on each specimen, one attached between the head and the copper block, the other between the copper contactor and the copper block. The difference between the two readings was expected to give the temperature difference. An additional correction is necessary, however. This arises from the manner of attaching the thermocouples to the heads. In Fig. 5 it is seen that the thermocouple recess extends about 3/8 inch above the bottom of the head. A temperature gradient may exist along the head due to heat conduction and cause the thermocouples to read a larger ΔT than actually exists. This gradient may be estimated by equation (12), with L approximately 0.375 inch and the area of heat flow being $(\pi/4)\,(0.375 \times 2.54)^2\ \mathrm{cm}^2$. For the values of Q used (0.03 to 0.08) this gives a correction of about 0.02°C, which was used for all points. The true ΔT was then

$$\Delta T = \Delta T_m - \Delta T_g - 0.02 \qquad (26)$$

where ΔT_m is the temperature difference between the head and the copper block and ΔT_g is the temperature drop across the Vaseline film. The thermal conductivity was then calculated from equation (12). For example, the data for brass at 79.88°K from Tables are: $\Delta T_m = 2.429°$, $\Delta T_g = 0.059°$, $q_{corr} = 0.03285$ watts and L/A is calculated to be 31.627/cm. Then

$$k_{brass} = 31.627 \, \frac{0.03285}{2.429 - 0.059 - 0.02} = 0.442 \text{ watt/cm°C} \qquad (27)$$

There is a further correction due to a slow rise in the temperature of the head and specimen during the measurements, as discussed on p 194. Equation (21) gives the magnitude of the correction, which can be expressed as

$$k' = k\ (1 - F) \tag{28}$$

in which k is the thermal conductivity from equation (27), k' is the correct value for the thermal conductivity and (1 - F) is the quantity in brackets in equation (21). F can be evaluated as follows. The heads were weighed and found to have a mass of about 16 grams each. The calculated weight of the specimens is 8.0 grams for brass and 8.7 grams for cadmium. Then

$$F = \frac{a}{60\ Q_o}\left[16\ C_H + \frac{M_S\ C_S}{2}\right] \tag{29}$$

where M_S is 4.0 for brass, 4.35 for cadmium, and 60 is the conversion factor between minutes and seconds. The quantities used in the calculations and the results obtained are in Tables 8 and 9, which are self explanatory.

Thermal conductivity of Vaseline. --The thermal conductivity of Vaseline could be estimated from the experimental arrangement of the brass and cadmium specimens, as explained in Chapter IV. The heat flow across the film was the same as that through the specimen and the temperature drop ΔT_g was measured by a three junction copper-constantan thermocouple. It seems reasonable to estimate the thickness of the film as 0.001 inch as this is the radial clearance between the copper contactors and the hole in the copper block. The area A was estimated as

$$A = (\pi/4)\,(d^2) + \pi d\,h \tag{30}$$

where d is the diameter of the copper contactor (3/8 inch) and h its length (1 inch). The area is then 8.3 cm^2. The thermal conductivity of the Vaseline calculated by equation (12) is found in Table 10 and Fig. 11.

Thermal conductivity of copper.--The thermal conductivity of copper was computed from the ΔT and Q_o measured in the calibration of the thermocouples and the length and area of the specimen. The ΔT was corrected for drop across the Vaseline film by assuming a 0.001 inch thick film and an area of $(\pi/4)\,(0.375)^2 + 0.375\ (1.875) = 2.31\ in^2 = 14.9\ cm^2$. The measured ΔT was about 0.015°C too high, as discussed above. Therefore,

$$\Delta T_c = \Delta T_m - \Delta T_g - 0.015 \tag{31}$$

where ΔT_c is the correct ΔT, ΔT_m is the measured ΔT and ΔT_g is the ΔT calculated for the Vaseline film. The correction due to drift rate discussed above was applied. The results are in Table 11 and Fig. 12.

The fact that a minimum in the conductivity of both copper and cadmium appears in this work may indicate that a similar minimum will be found in specimens of high conductivity. If this is true, however, it is surprising that no minimum appeared in the conductivity of brass, as its conductivity is the same order of magnitude over most of the range studied.

TABLE 8

Drift Rate Correction for Brass

Explanation:

T_B	= Temperature of copper block + 1/2 ΔT_m
ΔT_m	= Temperature difference, head to copper block
C_H	= Specific heat of copper head, joules
C_S	= Specific heat of specimen, joules, (based on composition of 62 Cu, 35 Zn, 3 Pb)
a	= Drift rate, °C/min.
F	= See equation (29)
k(1-F)	= k' (See Table 2) watts/cm-°C

T_B	C_H	C_S	10^3a	10^2F	k(1-F)
79.88	0.208	0.220	8.3	1.77	0.434
92.40	0.234	0.247	6.6	1.45	0.470
113.36	0.278	0.284	4.5	1.10	0.542
133.44	0.304	0.314	3.8	0.88	0.610
158.78	0.330	0.345	1.1	0.28	0.708
177.60	0.346	0.364	1.4	0.31	0.774
198.01	0.358	0.381	1.4	0.31	0.855
217.34	0.365	0.395	1.7	0.31	0.940
240.84	0.373	0.412	0.5	0.09	1.05
256.64	0.377	0.420	0.7	0.11	1.11
275.36	0.381	0.432	1.5	0.25	1.18

TABLE 9

Drift Rate Correction for Cadmium

Explanation:

See Table 8

See Table 8 for values of C_H

Tm°K	C_S	10^3a	10^2F	k(1 - F)
81.51	0.184	17	1.52	0.940
92.83	0.193	16	1.58	0.926
113.92	0.204	12	1.42	0.914
133.64	0.210	8	1.13	0.918
159.26	0.217	6	0.80	0.930
177.79	0.219	4	0.62	0.941
198.18	0.221	4	0.68	0.966
217.36	0.223	3	0.48	0.985
241.08	0.226	14	0.22	1.03
256.73	0.228	9	0.14	1.05
275.62	0.229	33	0.49	1.05

TABLE 10

Thermal Conductivity of Vaseline

Explanation:

T_B = Temperature of copper block, °K
Q_o = Heat input minus heat flow along leads, watts
ΔT_g = Temperature drop across Vaseline film, °C
k = Thermal conductivity of Vaseline, watts/cm-°C

T_B	Q_o	ΔT_g	10^4k
k as measured on brass specimen			
78.7	0.03285	0.059	1.82
91.2	0.03596	0.034	3.46
112.2	0.03970	0.019	6.82
132.3	0.04392	0.033	4.35
157.8	0.04387	0.040	3.58
176.5	0.05320	0.064	2.72
197.0	0.05424	0.069	2.57
216.2	0.06730	0.090	2.44
239.8	0.06785	0.076	2.96
255.5	0.07934	0.084	3.09
274.3	0.07795	0.079	3.22
k as measured on cadmium specimen			
79.2	0.07720	0.181	1.39
91.5	0.07734	0.168	1.50
112.6	0.07536	0.135	1.82
132.5	0.06797	0.116	1.91
158.0	0.07334	0.117	2.05
176.6	0.06955	0.107	2.12
197.1	0.06511	0.092	2.31
216.2	0.07092	0.080	2.89
239.9	0.07439	0.074	3.28
255.6	0.07316	0.072	3.32
274.4	0.07999	0.069	3.78

TABLE 11

Thermal Conductivity of Copper

Explanation:

T_B	= Temperature of copper block + 1/2 ΔT_m, °K
ΔT_m	= Temperature difference, head to copper block, °K
Q_o	= Heat input, watts
ΔT_o	= Temperature difference, head to copper block, °C
ΔT_g	= Computed temperature drop across Vaseline film, °C
ΔT_c	= $\Delta T_o - \Delta T_g - 0.015$, °C
k	= Thermal conductivity calculated from Q_o and ΔT_c, watts/cm-°C
k'	= k corrected for drift rate

T_B	Q_o	ΔT_o	ΔT_g	ΔT_c	k	k'
Liquid nitrogen bath						
80.06	0.3133	2.900	0.382	2.503	4.44	4.23
95.34	0.2814	2.783	0.311	2.457	4.06	3.85
115.62	0.2810	2.912	0.258	2.639	3.78	3.58
135.53	0.2512	2.882	0.222	2.645	3.37	3.11
159.46	0.2516	2.715	0.208	2.492	3.58	3.46
181.56	0.2331	2.504	0.187	2.302	3.59	3.47
198.35	0.2330	2.467	0.171	2.281	3.62	3.50
217.30	0.2311	2.340	0.136	2.189	3.74	3.60
Dry ice-alcohol bath						
198.53	0.2300	2.424	0.169	2.240	3.64	3.53
220.90	0.2292	2.329	0.133	2.182	3.73	3.60
240.88	0.2290	2.277	0.119	2.143	3.79	3.66
257.38	0.2286	2.288	0.117	2.156	3.76	3.63
275.40	0.2554	2.520	0.115	2.390	3.79	3.65

TABLE 12

Drift Rate Correction for Copper

Explanation:

See Table 8

See Table 8 for values of C_H, which is also C_S

T_m	10^2a	10^2F	$k(1 - F)$
80.06	9.0	4.78	4.23
95.34	6.0	5.16	3.85
115.62	5.2	5.32	3.58
135.53	7.9	7.58	3.11
159.46	3.3	3.46	3.46
181.56	2.7	3.22	3.47
198.35	2.6	3.20	3.50
217.30	3.0	3.79	3.60
198.53	2.4	2.99	3.53
220.90	3.1	3.97	3.60
240.88	2.7	3.52	3.66
257.38	2.7	3.56	3.63
275.40	3.2	3.82	3.65

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